

# HOMOTOPY COLIMITS IN STABLE REPRESENTATION THEORY.

ANDREW SALCH

**ABSTRACT.** We study the problem of existence and uniqueness of homotopy colimits in stable representation theory, where one typically does not have model category structures to guarantee that these homotopy colimits exist or have good properties. We get both negative results (homotopy cofibers fail to exist if there exist any objects of positive finite projective dimension!) and positive results (reasonable conditions under which homotopy colimits exist and are unique, even when model category structures fail to exist). Along the way, we obtain relative-homological-algebraic generalizations of classical theorems of Hilton-Rees and Oort. We describe some applications to Waldhausen  $K$ -theory and to deformation-theoretic methods in stable representation theory.

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## 1. INTRODUCTION.

Suppose  $\mathcal{C}$  is an abelian category—for examples, the category of modules over a ring, or the category of abelian sheaves on a scheme. By *stable representation theory* one means the study of  $\mathcal{C}$  under the equivalence relation in which one regards two maps  $f, g$  in  $\mathcal{C}$  as being equivalent, or “homotopic,” if  $f - g$  factors through a projective object. One says that two objects in  $\mathcal{C}$  are “stably equivalent” if they become isomorphic after imposing this equivalence relation on maps in  $\mathcal{C}$ . Since stably equivalent objects in  $\mathcal{C}$  have the same  $\text{Ext}_{\mathcal{C}}^n$  groups for all  $n > 0$ , stable representation theory is a natural topic of study if one wants to compute the higher  $\text{Ext}_{\mathcal{C}}$  groups for a large family of objects (or perhaps *all* objects) in  $\mathcal{C}$ .

In this paper we consider the problem of the existence and uniqueness of *homotopy colimits* in stable representation theory. Specifically, if one has a diagram of objects in an abelian category  $\mathcal{C}$ , and all of the morphisms in the diagram are monomorphisms, one wants to know that replacing an object in the diagram with a stably equivalent object will not change the colimit of the diagram, up to stable equivalence. Here are some reasons why one wants to do this:

- One wants to study and compute the stable algebraic  $G$ -theory associated to  $\mathcal{C}$ , that is, one wants to study *derived stable representation theory*, in the sense that  $G_0(\mathcal{C})$  is the Grothendieck group completion of a monoid of stable equivalence classes of objects in  $\mathcal{C}$ , and the higher  $G$ -theory groups capture more subtle  $K$ -theoretic invariants of the stable representation theory of  $\mathcal{C}$ . We do some of this in our paper [12], using results from the present paper.

To construct the relevant  $G$ -theory, one needs the structure of a Waldhausen category on  $\mathcal{C}$  in which the weak equivalences are the stable equivalences. But one of the axioms required of a Waldhausen category, Waldhausen's axiom **Weq 2** from [13], is that, given a commutative diagram in  $\mathcal{C}$

$$\begin{array}{ccccc} X' & \longleftarrow & Y' & \longrightarrow & Z' \\ \downarrow & & \downarrow & & \downarrow \\ X & \longleftarrow & Y & \longrightarrow & Z \end{array}$$

in which the horizontal maps are cofibrations and the vertical maps are weak equivalences, the induced map of pushouts

$$X' \coprod_{Y'} Z' \rightarrow X \coprod_Y Z$$

is a weak equivalence. In other words, *homotopy pushouts are well-defined in  $\mathcal{C}$* . So one must know something about well-definedness of homotopy pushouts in order to do any  $K$ -theory or  $G$ -theory.

- One wants to be able to make constructions in stable representation theory which come from *geometric realization of simplicial objects* and *totalization of cosimplicial objects*. For example, topological Hochschild homology and topological Andre-Quillen homology occur as geometric realizations, while topological Hochschild cohomology and topological Andre-Quillen cohomology occur as totalizations. Cocycles classifying deformations of modules and algebras live in topological Hochschild cohomology and topological Andre-Quillen cohomology groups, and if one wants to use deformation-theoretic methods in stable representation theory, one wants to be able to form the necessary totalizations.

Meanwhile, topological Andre-Quillen homology occurs as homology of cotangent complexes, which also has applications in deformation theory, while under certain conditions, topological Hochschild homology receives a trace map from algebraic  $K$ -theory which is quite useful for making  $K$ -theory computations. So one wants to be able to form the necessary geometric realizations to construct these objects.

Geometric realizations are particular kinds of homotopy colimits and we study their existence and uniqueness in this paper. On the other hand, totalizations are homotopy limits, not colimits, so we put off their question of their existence and uniqueness in stable representation theory for a later paper.

Existence and uniqueness of homotopy colimits is well-understood in the context of a model category, but *abelian categories frequently do not admit the structure of a model category* in which the weak equivalences are the stable equivalences and the cofibrations are the monomorphisms! So one cannot rely on general model-category-theoretic methods.

In fact, we get some negative results, which preclude the existence of such a model category structure (or even a Waldhausen category structure) on an abelian category under surprising conditions: a special case of our Cor. 3.11 is that *if an abelian category  $\mathcal{C}$  with*

*enough projectives has any objects of finite, positive projective dimension, then homotopy cofibres fail to be well-defined in  $\mathcal{C}$ .* As a consequence, if there exists a single object of projective dimension  $\neq 0, \infty$ , then  $\mathcal{C}$  cannot have a model category structure or a Waldhausen category structure with the desired cofibrations and weak equivalences!

On the other hand, suppose that  $\mathcal{C}$  has enough projectives and enough injectives, and suppose that every projective object is injective. Then homotopy cofibers (and homotopy pushouts in general) are unique up to stable equivalence; this is a special case of our Cor. 4.4. As a consequence,  $\mathcal{C}$  then satisfies Waldhausen's axiom **Weq 2**. This is substantially weaker than the assumption that  $\mathcal{C}$  is quasi-Frobenius (i.e., projective objects coincide with injective objects), which is the known condition under which  $\mathcal{C}$  admits a model category structure with the desired properties, as in [4].

We also show that, when  $\mathcal{C}$  has enough projectives and enough injectives, when every projective object is injective, and when every object can be embedded appropriately into a projective object, then geometric realization of simplicial objects is well-defined in  $\mathcal{C}$ ; this is a special case of our Cor. 6.8.

Throughout this paper, we work not just with abelian categories, but with abelian categories with a specified *allowable class*; that is, we work in the context of *relative homological algebra*. A good treatment of the basics of this subject is in Mac Lane's book [6], but the appendix to this paper is a self-contained introduction to the subject, so that the reader will not have to look elsewhere for the basic definitions.

There are two reasons we work in the context of relative homological algebra:

- One wants to study the effect of localization, i.e., change of allowable class, on algebraic  $G$ -theory. In [12] we use such localization methods to obtain some long exact sequences in stable algebraic  $G$ -theory groups, i.e., derived stable representation groups, of Hopf algebras. Our results in [12] require the results on well-definedness of homotopy pushouts, in particular Cor. 4.5, from the present paper.
- Our main area of applications for these results is in the stable representation theory of comodules over Hopf algebroids, especially those arising in stable homotopy theory. The Ext groups in the category of comodules over various Hopf algebroids are the  $E_2$ -terms of generalized Adams spectral sequences which are used to compute stable homotopy groups of various spaces and spectra, so the stable representation theory of these comodules is quite important for topology. If  $(A, \Gamma)$  is a Hopf algebroid, the relevant homological algebra is the one in which the relative projective objects are the comodules which are tensored up from  $A$ -modules; see Appendix 1 of [11] for these ideas. Since comodules over certain Hopf algebroids are equivalent to quasicohherent modules over certain Artin stacks, this direction is relevant to algebraic geometry as well.

We note that three essential technical tools in this paper are the relative-homological-algebraic generalizations of classical theorems in the theory of abelian categories: namely, our Lemmas 3.6 and 3.7 are the relative versions of the main results of the 1961 paper [3] of Hilton and Rees, and our Prop. 4.1 is the relative version of the main result of the 1963 paper [9] of Oort. These generalizations are, to our knowledge, new, but they are not difficult: one can simply mimic the proofs of Hilton-Rees and Oort, with appropriate adjustments for the more general setting.

Even if one has no interest in relative homological algebra or in abelian categories aside from categories of modules over a ring, our positive results still have some "teeth": there is an open conjecture in pure algebra that the category of finitely-generated modules over a ring  $R$  is quasi-Frobenius if and only if every finitely-generated  $R$ -module embeds in a

projective  $R$ -module. See [10] for some discussion of this problem. This conjecture is the analogue for *finitely-generated* modules of the theorem of Faith and Walker (a good reference is [2]), which states that the category of *all*  $R$ -modules is quasi-Frobenius if and only if every  $R$ -module embeds in a projective  $R$ -module. The main point of the section on homotopy pushouts and homotopy cofibres in the present paper is that one weakening of the (relative) quasi-Frobenius condition—the condition that every relatively projective object be relatively injective—suffices to ensure that homotopy pushouts are well-defined. This result is Prop. 4.4. So if one wants to study the stable representation theory of *finitely-generated*  $R$ -modules (which is what one must do in order for  $K$ -theoretic approaches like stable  $G$ -theory to be applicable, to avoid an Eilenberg swindle forcing all  $K$ -groups to be trivial!), then being able to embed such modules in projectives is *not* known to imply the quasi-Frobenius property and hence such module categories are *not* known to admit the structure of a model category—but one still has some good properties (e.g. homotopy cofibres, and Waldhausen’s axiom **Weq 2**) in such categories of modules, by the results in the present paper.

Finally, we list the main results in this paper, for ease of reference:

- Cor. 3.11 states that, in a relative abelian category with enough relative projectives and in which there exists an object of positive, finite relative projective dimension, homotopy pushouts (including homotopy cofibers) fail to be unique up to homotopy equivalence.
- Cor. 3.12 states that, under the same hypotheses, such a relative abelian category does not satisfy Waldhausen’s axiom **Weq 2**.
- Prop. 4.4 states that, under mild assumptions on a relative abelian category, if every relatively projective object is relatively injective, then homotopy pushouts (including homotopy cofibers) *are* unique up to homotopy equivalence.
- Cor. 4.5 states that, under the same hypotheses, the relative abelian category *does* satisfy Waldhausen’s axiom **Weq 2**.
- Prop. 5.2 states that, under mild assumptions on a relative abelian category, if every relatively projective object is relatively injective, then sequential homotopy colimits are unique up to homotopy equivalence.
- Cor. 6.8 states that, under the same hypotheses, if the abelian category is AB3 and every object embeds appropriately in a relatively projective object, then geometric realizations of simplicial objects exist and are unique up to homotopy equivalence.

## 2. DEFINITIONS.

We define a category with a minimal amount of structure one wants in order to consider the notion of homotopy colimits therein:

**Definition 2.1.** *By a weak Waldhausen category we mean a category  $C$  equipped with a pair of subcategories  $\text{cof}(C)$ ,  $\text{we}(C)$  of  $C$  such that:*

- *For each object  $X$  of  $C$ , the identity map on  $X$  is in both  $\text{cof}(C)$  and  $\text{we}(C)$ . (In other words,  $\text{cof}(C)$  and  $\text{we}(C)$  are both “*lluf*.”)*

The notion of a weak Waldhausen category is so general and so weakly-structured that one can’t hope to prove much about such objects. Using some ideas from relative homological algebra, we now define a particular class of weak Waldhausen categories that we can actually prove some things about:

**Definition 2.2.** By a weak Waldhausen abelian category we mean an abelian category  $C$  equipped with the structure of a weak Waldhausen category, and such that there exists an allowable class  $E$  in  $C$  with the property that:

- $we(C)$  is equal to the class of  $E$ -stable equivalences, and
- $cof(C)$  is equal to the class of  $E$ -monomorphisms.

If  $E$  is such an allowable class for a given weak Waldhausen abelian category  $C$ , we will say that  $E$  is allowable for  $C$ .

The appendix to this paper provides some useful classical definitions for the reader unfamiliar with relative homological algebra. In particular, “allowable class” is Def. 7.1 and “ $E$ -stable equivalence” is Def. 7.5.

The following is Waldhausen’s axiom **Weq 2**, which we will be concerned with:

**Definition 2.3.** Let  $C$  be a weak Waldhausen category. We say that  $C$  satisfies Waldhausen’s axiom **Weq 2** if, for each commutative diagram

$$\begin{array}{ccccc} X' & \longleftarrow & Y' & \longrightarrow & Z' \\ \downarrow & & \downarrow & & \downarrow \\ X & \longleftarrow & Y & \longrightarrow & Z \end{array}$$

in which the maps  $Y' \rightarrow X'$  and  $Y \rightarrow X$  are cofibrations and the vertical maps are all weak equivalences, then the map

$$X' \coprod_{Y'} Z' \rightarrow X \coprod_Y Z$$

is a weak equivalence.

**Definition 2.4.** Let  $\mathcal{D}$  be a small category and let  $C$  be a category with a distinguished class of morphisms  $cof(C)$  (for example,  $C$  could be a weak Waldhausen abelian category). Suppose  $C$  has an initial object  $0$ . By a  $\mathcal{D}$ -indexed homotopy colimit diagram in  $C$  we mean a functor  $F : \mathcal{D} \rightarrow C$  with the following properties:

- For each object  $X$  of  $\mathcal{D}$ , the map  $0 \rightarrow F(X)$  is in  $cof(C)$ .
- For each map  $f : X \rightarrow Y$  in  $\mathcal{D}$ , the map  $F(f) : F(X) \rightarrow F(Y)$  is in  $cof(C)$ .

We shall see, in Lemma 3.4, that if  $C$  is a weak Waldhausen abelian category with an allowable class that has sectile epics, then the first condition (that the map  $0 \rightarrow F(X)$  be a cofibration) in Def. 2.4 is actually redundant—it is automatically satisfied. The second condition in Def. 2.4 is the significant one. See Def. 7.6 for the definition of “having sectile epics.”

**Definition 2.5.** Let  $\mathcal{D}$  be a small category and let  $C$  be a weak Waldhausen abelian category. Suppose  $E$  is a class allowable for  $C$ . We say that  $\mathcal{D}$ -indexed homotopy colimits of  $E$ -projectives in  $C$  are  $E$ -projective if, whenever  $F : \mathcal{D} \rightarrow C$  is a homotopy colimit diagram such that  $F(X)$  is  $E$ -projective for every object  $X$  of  $\mathcal{D}$ , the colimit  $\text{colim } F$  exists and is  $E$ -projective.

The essential property that one wants in a homotopy colimit is that it should be homotopy-invariant. In a model category, one always knows that this is so. But in our much, much more general situation, that of a weak Waldhausen abelian category, some homotopy colimit diagrams may fail to have homotopy-invariant colimits. When this is so, we say that the homotopy colimit in question *fails to be well-defined*. Precisely:

**Definition 2.6.** Let  $\mathcal{D}$  be a small category and let  $\mathcal{C}$  be a weak Waldhausen abelian category. Suppose  $\mathcal{C}$  has all  $\mathcal{D}$ -indexed colimits (e.g.  $\mathcal{C}$  is an AB3, that is, co-complete, abelian category). We say that  $\mathcal{D}$ -indexed homotopy colimits are well-defined, or unique up to homotopy, in  $\mathcal{C}$  if, for any pair of  $\mathcal{D}$ -indexed homotopy colimit diagrams  $F, G : \mathcal{D} \rightarrow \mathcal{C}$  and any map of diagrams  $\phi : F \rightarrow G$  such that  $\phi(X) : F(X) \rightarrow G(X)$  is in  $we(\mathcal{C})$  for every object  $X$  of  $\mathcal{D}$ , the induced map  $\text{colim } F \rightarrow \text{colim } G$  is in  $we(\mathcal{C})$ .

Finally, we include definitions related to lengths of  $E$ -projective resolutions, which we will use in the next section:

**Definition 2.7.** Suppose  $\mathcal{C}$  is an abelian category,  $E$  an allowable class in  $\mathcal{C}$ . We say that a long exact sequence

$$\cdots \xrightarrow{f_n} P_{n-1} \xrightarrow{f_{n-1}} \cdots \xrightarrow{f_1} P_0 \xrightarrow{f_0} X \rightarrow 0$$

is  $E$ -long exact if each short exact sequence

$$0 \rightarrow \ker f_{i+1} \rightarrow P_i \rightarrow \text{coker } f_{i+1} \rightarrow 0$$

is in  $E$ . If each  $P_i$  is an  $E$ -projective object, we say that the  $E$ -long exact sequence is an  $E$ -projective resolution of  $X$ .

**Definition 2.8.** Suppose  $\mathcal{C}$  is an abelian category,  $E$  an allowable class in  $\mathcal{C}$ . Suppose  $n$  is a nonnegative integer. We say that an object  $X$  of  $\mathcal{C}$  has  $E$ -projective dimension  $\leq n$  if there exists an  $E$ -projective resolution of  $X$

$$0 \rightarrow P_n \xrightarrow{f_n} P_{n-1} \xrightarrow{f_{n-1}} \cdots \xrightarrow{f_1} P_0 \xrightarrow{f_0} X \rightarrow 0.$$

We say that  $X$  has  $E$ -projective dimension  $n$  if it has  $E$ -projective dimension  $\leq n$  but does not have  $E$ -projective dimension  $\leq n - 1$ .

### 3. NEGATIVE RESULTS ON ALL HOMOTOPY COLIMITS.

In this section we prove that homotopy colimits in a weak Waldhausen abelian category fail to be unique up to homotopy unless colimits of appropriately-shaped relative projectives are themselves relatively projective. A precise statement is in Prop. 3.10. An important application of Prop. 3.10 is the case of homotopy pushouts (and, in particular, homotopy cofibers) in Cor. 3.11, and the question of whether Waldhausen's axiom **Weq 2** is satisfied, which we address in Cor. 3.12.

We begin by proving some lemmas that will allow us to prove both well-definedness and non-well-definedness results about homotopy colimits.

**Lemma 3.1.** Let  $\mathcal{C}$  be an abelian category and let  $E$  be an allowable class in  $\mathcal{C}$ . Suppose  $\mathcal{C}$  has enough  $E$ -projectives. Then an object  $X$  of  $\mathcal{C}$  is  $E$ -projective if and only if  $\text{Ext}_{\mathcal{C}/E}^1(X, Y) \cong 0$  for all objects  $Y$  of  $\mathcal{C}$ .

*Proof.* Suppose  $X$  is  $E$ -projective. Then vanishing of  $\text{Ext}_{\mathcal{C}/E}^1(X, Y)$  is classical (and easy).

Now suppose  $X$  is not  $E$ -projective. Then there exists some  $E$ -epimorphism  $f : A \rightarrow B$  and a map  $g : X \rightarrow B$  which does not lift through  $f$ . In other words, the element  $g \in \text{hom}_{\mathcal{C}}(X, B)$  is not in the image of the map

$$\text{hom}_{\mathcal{C}}(X, A) \rightarrow \text{hom}_{\mathcal{C}}(X, B).$$

But we have the exact sequence

$$\text{hom}_{\mathcal{C}}(X, A) \rightarrow \text{hom}_{\mathcal{C}}(X, B) \rightarrow \text{Ext}_{\mathcal{C}/E}^1(X, \ker f)$$

and so  $g$  must have nonzero image in  $\text{Ext}_{C/E}^1(X, \ker f)$ . So  $\text{Ext}_{C/E}^1(X, \ker f)$  is nontrivial. So by contrapositive, vanishing of  $\text{Ext}_{C/E}^1(X, Y)$  for all  $Y$  implies that  $X$  is  $E$ -projective.  $\square$

**Lemma 3.2.** *Suppose  $C$  is an abelian category,  $E$  an allowable class in  $C$  with sectile epics. Suppose  $C$  has enough  $E$ -projectives. Then any finite direct sum of members of  $E$  is in  $E$ .*

*Proof.* Let  $I$  be a finite set and

$$0 \rightarrow X_i \rightarrow Y_i \rightarrow Z_i \rightarrow 0$$

be a member of  $E$  for every  $i \in I$ . Then, for any  $E$ -projective object  $P$  of  $C$ , we have the commutative diagram

$$\begin{array}{ccc} \text{hom}_C(P, \oplus_i Y_i) & \longrightarrow & \text{hom}_C(P, \oplus_i Z_i) \\ \downarrow \cong & & \downarrow \cong \\ \oplus_i \text{hom}_C(P, Y_i) & \longrightarrow & \oplus_i \text{hom}_C(P, Z_i). \end{array}$$

The bottom horizontal map is a surjection of abelian groups, so the top horizontal map is as well. Now by Heller's theorem 7.7, the map  $\oplus_i Y_i \rightarrow \oplus_i Z_i$  is an  $E$ -epimorphism. So the short exact sequence

$$0 \rightarrow \oplus_i X_i \rightarrow \oplus_i Y_i \rightarrow \oplus_i Z_i \rightarrow 0$$

is in  $E$ .  $\square$

**Lemma 3.3. (Shearing  $E$ -monics.)** *Let  $C$  be an abelian category and let  $E$  be an allowable class in  $C$ . Suppose  $X, Y, Z$  are objects in  $C$  and suppose we have  $E$ -monomorphisms  $e : X \rightarrow Y$  and  $f : Z \rightarrow Y$ . Let  $s$  be the morphism*

$$s : X \oplus Z \rightarrow Y \oplus Z$$

*given by the matrix of maps*

$$s = \begin{bmatrix} e & 0 \\ f & \text{id}_Z \end{bmatrix}.$$

*Then  $\text{coker } s$  is naturally isomorphic to  $\text{coker } e$ . Furthermore, if  $C$  has enough  $E$ -injectives and  $E$  has retractile monics, then  $s$  is an  $E$ -monomorphism.*

*Proof.* We first show that  $\text{coker } e \cong \text{coker } s$ . But this follows immediately from the commutative diagram with exact rows and exact columns:

$$\begin{array}{ccccccccc} 0 & \longrightarrow & 0 & \longrightarrow & 0 & \longrightarrow & 0 & \longrightarrow & 0 \\ \downarrow & & \downarrow & & \downarrow & & \downarrow & & \downarrow \\ 0 & \longrightarrow & X & \xrightarrow{e} & Y & \longrightarrow & \text{coker } e & \longrightarrow & 0 \\ \downarrow & & \downarrow i & & \downarrow i & & \downarrow & & \downarrow \\ 0 & \longrightarrow & X \oplus Z & \xrightarrow{s} & Y \oplus Z & \longrightarrow & \text{coker } s & \longrightarrow & 0 \\ \downarrow & & \downarrow \pi & & \downarrow \pi & & \downarrow & & \downarrow \\ 0 & \longrightarrow & Z & \xrightarrow{\text{id}} & Z & \longrightarrow & 0 & \longrightarrow & 0 \\ \downarrow & & \downarrow & & \downarrow & & \downarrow & & \downarrow \\ 0 & \longrightarrow & 0 & \longrightarrow & 0 & \longrightarrow & 0 & \longrightarrow & 0 \end{array}$$

in which the maps marked  $\pi$  are projections to the second summand, and the maps marked  $i$  are inclusions as the first summand.

Now assume that  $E$  has retractile monics, and let  $t : Y \oplus Z \rightarrow Y \oplus Y$  be the map given by the matrix of maps

$$t = \begin{bmatrix} \text{id}_Y & 0 \\ -f & f \end{bmatrix}.$$

Then a matrix multiplication reveals that the composite map  $t \circ s : X \oplus Z \rightarrow Y \oplus Y$  is the direct sum map  $e \oplus f$ , a direct sum of  $E$ -monomorphisms, hence by Lemma 3.2, itself an  $E$ -monomorphism. (Note that, by taking the opposite category and noticing that the definition of an allowable class in an abelian category is self-dual, we get the conclusion of Lemma 3.2 if  $E$  has retractile monics and  $C$  has enough  $E$ -injectives.) Now since  $t \circ s$  is an  $E$ -monomorphism and  $E$  is assumed to have retractile monics,  $s$  is also an  $E$ -monomorphism.  $\square$

**Lemma 3.4.** *Suppose  $C$  is an abelian category,  $E$  an allowable class in  $C$  which has sectile epics. Suppose  $C$  has enough  $E$ -projectives. Any split monomorphism in  $C$  is an  $E$ -monomorphism. Furthermore, any split epimorphism in  $C$  is an  $E$ -epimorphism.*

*Proof.* Any split monomorphism  $f$  fits into a short exact sequence

$$(3.1) \quad 0 \rightarrow X \xrightarrow{f} Y \rightarrow \text{coker } f \rightarrow 0$$

in which  $Y$  decomposes as  $X \oplus \text{coker } f$ , i.e., short exact sequence 3.1 is a direct sum of the short exact sequences

$$0 \rightarrow X \rightarrow X \rightarrow 0 \rightarrow 0$$

and

$$0 \rightarrow 0 \rightarrow \text{coker } f \rightarrow \text{coker } f \rightarrow 0,$$

both of which are in  $E$  by the definition of an allowable class. Now by Lemma 3.2, short exact sequence 3.1 is in  $E$ . So  $f$  is an  $E$ -monomorphism.

A totally analogous argument proves the same statement for split epimorphisms being  $E$ -epimorphisms.  $\square$

**Lemma 3.5.** *Suppose  $C$  is an abelian category,  $E$  an allowable class in  $C$  with sectile epics. Suppose  $C$  has enough  $E$ -projectives. A composite of  $E$ -epimorphisms is an  $E$ -epimorphism.*

*Proof.* Let  $f : X \rightarrow Y$  and  $g : Y \rightarrow Z$  be  $E$ -epimorphisms. Let  $P$  be an  $E$ -projective object equipped with a map  $P \rightarrow Z$ . Then, since  $g$  is an  $E$ -epimorphism,  $P \rightarrow Z$  lifts over  $g$  to a map  $P \rightarrow Y$ , which in turn lifts over  $f$  since  $f$  is an  $E$ -epimorphism. So every map from an  $E$ -projective to  $Z$  lifts over  $g \circ f$ . Now, by Heller's theorem 7.7,  $g \circ f$  is an  $E$ -epimorphism.  $\square$

The following two lemmas are the relative-homological-algebraic generalizations of the main results of Hilton and Rees's paper [3]. We provide proofs, but they are fairly easy generalizations of those already in the literature.

**Lemma 3.6.** *Suppose  $C$  is an abelian category with an allowable class  $E$ . Suppose  $C$  has enough  $E$ -projectives. Then  $E$ -stable equivalence classes of morphisms  $X \rightarrow Y$  in  $C$  are in bijection with natural transformations of functors*

$$\text{Ext}_{C/E}^1(Y, -) \rightarrow \text{Ext}_{C/E}^1(X, -).$$

*This bijection is natural in  $X$  and  $Y$ .*



*Proof.* This proof is a straightforward generalization of Margolis' proof of the Hilton-Rees result, as in Prop. 9 of section 14.1 of [8]. Write  $[X, Y]$  for  $\text{hom}_C(X, Y)$  modulo  $E$ -stable equivalence. We have the morphism of abelian groups

$$\alpha : \text{hom}_C(X, Y) \rightarrow \text{nat}(\text{Ext}_{C/E}^1(Y, -), \text{Ext}_{C/E}^1(X, -))$$

defined by the functoriality of  $\text{Ext}_{C/E}^1$  in the first variable. If  $f : X \rightarrow Y$  factors through a  $E$ -projective then clearly  $\alpha(f) = 0$ , so  $\alpha$  factors as

$$\begin{array}{ccc} \text{hom}_C(X, Y) & \xrightarrow{\alpha} & \text{nat}(\text{Ext}_{C/E}^1(Y, -), \text{Ext}_{C/E}^1(X, -)) \\ & \searrow & \nearrow \beta \\ & [X, Y] & \end{array}$$

We now check that  $\beta$  is a bijection. Suppose  $\beta(f) = 0$ . Then choose  $E$ -projective covers  $s_X : PX \rightarrow X$  and  $s_Y : PY \rightarrow Y$ . We have the commutative diagram with exact rows

$$(3.2) \quad \begin{array}{ccccccccc} 0 & \longrightarrow & \ker s_X & \xrightarrow{i_X} & PX & \xrightarrow{s_X} & X & \longrightarrow & 0 \\ & & \downarrow \ker s_f & \swarrow \ell & \downarrow Pf & & \downarrow f & & \downarrow \\ 0 & \longrightarrow & \ker s_Y & \xrightarrow{i_Y} & PY & \xrightarrow{s_Y} & Y & \longrightarrow & 0. \end{array}$$

(The map as in the dotted line has not yet been shown to exist.) After applying  $\text{hom}_C(-, \ker s_Y)$ , we have the commutative diagram with exact rows

$$\begin{array}{ccccccc} 0 & \longleftarrow & \text{Ext}_{C/E}^1(X, \ker s_Y) & \longleftarrow & \text{hom}_C(\ker s_X, \ker s_Y) & \xleftarrow{\phi} & \text{hom}_C(PX, \ker s_Y) \\ \uparrow & & \uparrow 0 & & \uparrow \lambda & & \uparrow \\ 0 & \longleftarrow & \text{Ext}_{C/E}^1(Y, \ker s_Y) & \longleftarrow & \text{hom}_C(\ker s_Y, \ker s_Y) & \longleftarrow & \text{hom}_C(PY, \ker s_Y) \end{array}$$

Commutativity of the diagram together with exactness of the rows and triviality of the far left-hand vertical map implies that the map  $\lambda$  factors through the image of  $\phi$ , i.e., there exists a map  $\ell$  as in the dotted line in diagram 3.2 making the triangle involving  $\ker s_f$ ,  $i_X$ , and  $\ell$  commute. We now replace  $Pf$  with  $g = Pf - i_Y \circ \ell$  to get the commutative diagram with exact rows

$$(3.3) \quad \begin{array}{ccccccccc} 0 & \longrightarrow & \ker s_X & \xrightarrow{i_X} & PX & \xrightarrow{s_X} & X & \longrightarrow & 0 \\ & & \downarrow \ker s_f & & \downarrow g & \swarrow \mu & \downarrow f & & \\ 0 & \longrightarrow & \ker s_Y & \xrightarrow{i_Y} & PY & \xrightarrow{s_Y} & Y & \longrightarrow & 0. \end{array}$$

Since  $g \circ i_X = Pf \circ i_X - i_Y \circ \ell \circ i_X = 0$ , there exists a map as in the dotted line in diagram 3.3 to make the triangle involving  $s_X$ ,  $g$ , and  $\mu$  commute. Now we have

$$\begin{aligned} f \circ s_X &= s_Y \circ g \\ &= s_Y \circ \mu \circ s_X \end{aligned}$$

and  $s_X$  is  $E$ -epic, hence epic, i.e., right-cancellable, so  $f = s_Y \circ \mu$ . So  $f$  factors through the  $E$ -projective  $PY$ , i.e.,  $f$  is  $E$ -stably equivalent to zero. So  $\beta$  is one-to-one.

Now choose a natural transformation  $\text{Ext}_{C/E}^1(Y, -) \rightarrow \text{Ext}_{C/E}^1(X, -)$ . We choose  $E$ -projective covers  $s_X : PX \rightarrow X$  and  $s_Y : PY \rightarrow Y$  as above. Write  $\chi \in \text{Ext}_{C/E}^1(Y, \ker s_Y)$  for the class of the extension

$$0 \rightarrow \ker s_Y \rightarrow PY \rightarrow Y \rightarrow 0.$$

Notice that the natural map  $\text{hom}_C(\ker s_X, \ker s_Y) \rightarrow \text{Ext}_{C/E}^1(X, \ker s_Y)$  is surjective since  $PX$  is  $E$ -projective and hence  $\text{Ext}_{C/E}^1(PX, \ker s_Y) \cong 0$ . So we can choose an element  $h \in \text{hom}_C(\ker s_X, \ker s_Y)$  whose image in  $\text{Ext}_{C/E}^1(X, \ker s_Y)$  agrees with the image of  $\chi$  under the given map

$$\text{Ext}_{C/E}^1(Y, \ker s_Y) \rightarrow \text{Ext}_{C/E}^1(X, \ker s_Y).$$

The map  $\text{Ext}_{C/E}^1(Y, \ker s_Y) \rightarrow \text{Ext}_{C/E}^1(Y, PY)$  is automatically zero, so from the commutative diagram

$$\begin{array}{ccc} \text{Ext}_{C/E}^1(Y, \ker s_Y) & \xrightarrow{0} & \text{Ext}_{C/E}^1(Y, PY) \\ \downarrow & & \downarrow \\ \text{Ext}_{C/E}^1(X, \ker s_Y) & \longrightarrow & \text{Ext}_{C/E}^1(X, PY) \end{array}$$

we know that the image of  $\chi$  in  $\text{Ext}_{C/E}^1(X, PY)$  is zero. Hence also the image of  $h$  in  $\text{Ext}_{C/E}^1(X, PY)$  is zero. Hence in the commutative diagram with exact columns

$$\begin{array}{ccc} & \text{hom}_C(PX, PY) & \\ & \downarrow & \\ \text{hom}_C(\ker s_X, \ker s_Y) & \longrightarrow & \text{hom}_C(\ker s_X, PY) \\ \downarrow & & \downarrow \\ \text{Ext}_{C/E}^1(X, \ker s_Y) & \longrightarrow & \text{Ext}_{C/E}^1(X, PY) \end{array}$$

the image of  $h$  in  $\text{hom}_C(\ker s_X, PY)$  lifts to an element in  $\text{hom}_C(PX, PY)$ , i.e., we have a commutative diagram

$$\begin{array}{ccccccc} 0 & \longrightarrow & \ker s_X & \longrightarrow & PX & \longrightarrow & X \longrightarrow 0 \\ \downarrow & & \downarrow h & & \downarrow & & \downarrow \\ 0 & \longrightarrow & \ker s_Y & \longrightarrow & PY & \longrightarrow & Y \longrightarrow 0 \end{array}$$

and the map  $X \rightarrow Y$  is the desired map inducing the given natural transformation in  $\text{Ext}_{C/E}^1$ . Hence  $\beta$  is surjective, hence an isomorphism.  $\square$

**Lemma 3.7.** *Suppose  $C$  is an abelian category with an allowable class  $E$  with sectile epics. Suppose  $C$  has enough  $E$ -projectives. Then a map  $f : X \rightarrow Y$  in  $C$  induces a natural isomorphism*

$$(3.4) \quad \text{Ext}_{C/E}^1(Y, -) \rightarrow \text{Ext}_{C/E}^1(X, -)$$

*if and only if there exist  $E$ -projective objects  $P, Q$  and an isomorphism  $g : X \oplus P \rightarrow Y \oplus Q$  such that the composite*

$$X \xrightarrow{i} X \oplus P \xrightarrow{g} Y \oplus Q \xrightarrow{p} Y$$

*is equal to  $f$ . (Here we write  $i$  for inclusion of the first summand and  $p$  for projection to the first summand.)*

*Proof.* If an isomorphism  $g$  exists as described then we have natural isomorphisms

$$\begin{aligned}
 \mathrm{Ext}_{C/E}^1(Y, -) &\cong \mathrm{Ext}_{C/E}^1(Y, -) \oplus \mathrm{Ext}_{C/E}^1(Q, -) \\
 &\cong \mathrm{Ext}_{C/E}^1(Y \oplus Q, -) \\
 &\cong \mathrm{Ext}_{C/E}^1(X \oplus P, -) \\
 &\cong \mathrm{Ext}_{C/E}^1(X, -) \oplus \mathrm{Ext}_{C/E}^1(P, -) \\
 &\cong \mathrm{Ext}_{C/E}^1(X, -)
 \end{aligned}$$

as desired.

For the converse: suppose  $f : X \rightarrow Y$  induces the natural isomorphism 3.4. Then, by Lemma 3.6,  $f$  is an  $E$ -stable equivalence. So there exists a map  $g : Y \rightarrow X$  such that  $\mathrm{id}_X - g \circ f$  and  $\mathrm{id}_Y - f \circ g$  each factors through an  $E$ -projective object. Suppose  $P$  is an  $E$ -projective object and  $i : Y \rightarrow P$  and  $s : P \rightarrow Y$  maps in  $C$  such that  $s \circ i = \mathrm{id}_Y - f \circ g$ . Since  $C$  has enough  $E$ -projectives, we can choose  $P$  so that  $s$  is epic. Then we have a short exact sequence in  $E$

$$(3.5) \quad 0 \rightarrow \ker m \rightarrow X \oplus P \xrightarrow{m} Y \rightarrow 0$$

where  $m$  is the map given by the matrix of maps

$$m = \begin{bmatrix} f \\ s \end{bmatrix}.$$

That  $m$  is an  $E$ -epimorphism follows from it being the composite

$$X \oplus P \xrightarrow{n} X \oplus Y \xrightarrow{\pi} Y$$

where  $n$  is given by the matrix of maps

$$n = \begin{bmatrix} \mathrm{id}_X & f \\ 0 & s \end{bmatrix}$$

and  $\pi$  is the projection to the second summand;  $n$  is an  $E$ -epimorphism by the dual of Lemma 3.3,  $\pi$  is an  $E$ -epimorphism by Lemma 3.4, and  $m = \pi \circ n$  is an  $E$ -epimorphism by Lemma 3.5.

Since  $m$  is an  $E$ -epimorphism, by definition the short exact sequence 3.5 is in  $E$ . So short exact sequence 3.5 induces a natural long exact sequence in  $\mathrm{Ext}_{C/E}$  for any object  $M$  of  $C$ :

$$\begin{array}{ccccc}
 (3.6) & \mathrm{Ext}_{C/E}^i(X \oplus P, M) & & & \\
 & \uparrow \cong & & & \\
 & \mathrm{Ext}_{C/E}^i(Y, M) & \longleftarrow & \mathrm{Ext}_{C/E}^{i-1}(\ker m, M) & \longleftarrow & \mathrm{Ext}_{C/E}^{i-1}(X \oplus P, M) \\
 & & & & & \uparrow \cong \\
 & & & & & \mathrm{Ext}_{C/E}^{i-1}(Y, M)
 \end{array}$$

where the maps marked as isomorphisms are isomorphisms for  $i \geq 2$  since  $X \rightarrow Y$  is an  $E$ -stable equivalence. Exactness of long exact sequence 3.6 gives us that  $\mathrm{Ext}_{C/E}^{i-1}(\ker m, M) \cong 0$  for all  $M$  in  $C$  and all  $i \geq 2$ . So by Lemma 3.1,  $\ker m$  is an  $E$ -projective. Part of the long

exact sequence induced in  $\text{Ext}_{C/E}^1$  by short exact sequence 3.5 reads:

$$\begin{array}{ccccc}
 \text{Ext}_{C/E}^1(X \oplus P, M) & \xleftarrow{\cong} & \text{Ext}_{C/E}^1(Y, M) & & \\
 & \nearrow & & & \\
 \text{hom}_C(\ker m, M) & \xleftarrow{\quad} & \text{hom}_C(X \oplus P, M) & \xleftarrow{\quad} & \text{hom}_C(Y, M) \\
 & & & & \uparrow \\
 & & & & 0
 \end{array}$$

i.e.,

$$0 \rightarrow \text{hom}_C(Y, M) \rightarrow \text{hom}_C(X \oplus P, M) \rightarrow \text{hom}_C(\ker m, M) \rightarrow 0$$

is exact for every object  $M$  in  $C$ . Hence short exact sequence 3.5 is in fact *split*, and  $X \oplus P \cong Y \oplus \ker m$ , proving the lemma.  $\square$

**Lemma 3.8. (Shearing isomorphism.)** *Suppose  $X, Y$  are objects in an abelian category  $C$  and  $f : X \rightarrow Y$  is a monomorphism. Then the pushout  $Y \amalg_X Y$  is naturally isomorphic to  $Y \oplus \text{coker } f$ .*

*Proof.* Let  $g : Y \oplus Y \rightarrow Y \oplus Y$  be the map given by the (invertible, hence an isomorphism) matrix of maps

$$g = \begin{bmatrix} \text{id} & -\text{id} \\ 0 & \text{id} \end{bmatrix}.$$

Then we have the commutative diagram with exact rows

$$\begin{array}{ccccccccc}
 0 & \longrightarrow & X & \xrightarrow{[f \ f]} & Y \oplus Y & \longrightarrow & Y \amalg_X Y & \longrightarrow & 0 \\
 \downarrow & & \downarrow \text{id} & & \downarrow g & & \downarrow & & \downarrow \\
 0 & \longrightarrow & X & \xrightarrow{[f \ 0]} & Y \oplus Y & \longrightarrow & \text{coker } f \oplus Y & \longrightarrow & 0
 \end{array}$$

and hence the isomorphism  $Y \amalg_X Y \xrightarrow{\cong} \text{coker } f \oplus Y$ .  $\square$

**Lemma 3.9.** *Suppose  $C$  is an abelian category,  $E$  an allowable class in  $C$ . Suppose  $C$  has enough  $E$ -projectives. If there exists an object of finite  $E$ -projective dimension  $n \geq 2$  in  $C$ , then there exists an object of  $E$ -projective dimension 1 in  $C$ .*

*Proof.* Let  $X$  have  $E$ -projective dimension  $n \geq 2$ . Choose an  $E$ -projective resolution of  $X$

$$0 \rightarrow P_n \xrightarrow{f_n} P_{n-1} \xrightarrow{f_{n-1}} \cdots \xrightarrow{f_2} P_1 \xrightarrow{f_1} P_0 \rightarrow X \rightarrow 0.$$

Then

$$(3.7) \quad 0 \rightarrow P_n \xrightarrow{f_n} P_{n-1} \xrightarrow{f_{n-1}} \cdots \xrightarrow{f_2} P_2 \rightarrow \text{coker } f_2 \rightarrow 0$$

is an  $E$ -projective resolution of  $\text{coker } f_2$ . If  $\text{coker } f_2$  is  $E$ -projective, then

$$0 \rightarrow \text{coker } f_2 \rightarrow P_0 \rightarrow X \rightarrow 0$$

is a length 1  $E$ -projective resolution of  $X$ , and we are done. So suppose  $\text{coker } f_2$  is not  $E$ -projective. So it is not of  $E$ -projective dimension zero. Then diagram 3.7 expresses  $\text{coker } f_2$  as having  $E$ -projective dimension at most  $n - 1$ . Now we continue by induction: either  $\text{coker } f_3$  is  $E$ -projective or has  $E$ -projective dimension at most  $n - 2$ , etc. After at most  $n$  steps this process terminates with an object of  $E$ -projective dimension 1.  $\square$

The preceding lemmas suffice for us to prove the following proposition, which is really a negative result: it shows that, if  $\mathcal{D}$ -indexed colimits of  $E$ -projectives are not always  $E$ -projective, then  $\mathcal{D}$ -indexed homotopy colimits fail to be unique up to homotopy.

**Proposition 3.10.** *Let  $\mathcal{D}$  be a small category and let  $\mathcal{C}$  be a weak Waldhausen abelian category. Choose a class  $E$  allowable for  $\mathcal{C}$ . Suppose  $\mathcal{D}$ -indexed homotopy colimits are well-defined in  $\mathcal{C}$ . Then every  $\mathcal{D}$ -indexed colimit of  $E$ -projective objects of  $\mathcal{C}$  is  $E$ -projective.*

*Proof.* We work by contrapositive. Suppose there exists a homotopy colimit diagram  $F : \mathcal{D} \rightarrow \mathcal{C}$  with the property that  $F(X)$  is  $E$ -projective for every object  $X$  of  $\mathcal{D}$ , and  $\text{colim } F$  is not  $E$ -projective. Let  $G : \mathcal{D} \rightarrow \mathcal{C}$  be the zero diagram, i.e.,  $G(X) = 0$  for all objects  $X$  of  $\mathcal{D}$ . Then the unique map  $\phi : F \rightarrow G$  has the property that  $\phi(X)$  is an  $E$ -stable equivalence for every object  $X$  of  $\mathcal{D}$ , since any map with  $E$ -projective domain and  $E$ -projective codomain is trivially an  $E$ -stable equivalence. But  $\text{colim } F$  is nontrivial, so  $\text{Ext}_{\mathcal{C}/E}^1(\text{colim } F, Y)$  is nontrivial for some object  $Y$  of  $\mathcal{C}$ , by Lemma 3.1. So the natural transformation  $0 \cong \text{Ext}_{\mathcal{C}/E}^1(\text{colim } G, Y) \rightarrow \text{Ext}_{\mathcal{C}/E}^1(\text{colim } F, Y)$  is not an isomorphism. So by Lemma 3.6, the map  $\text{colim } F \rightarrow \text{colim } G \cong 0$  is not an  $E$ -stable equivalence.  $\square$

**Corollary 3.11.** *Let  $\mathcal{C}$  be a weak Waldhausen abelian category. Let  $E$  be a class allowable for  $\mathcal{C}$ . Suppose  $\mathcal{C}$  has enough  $E$ -projectives. Then homotopy pushouts, and in particular homotopy cofibers, are well-defined in  $\mathcal{C}$  only if every object in  $\mathcal{C}$  has  $E$ -projective dimension 0 or  $\infty$ .*

*Proof.* Suppose an object in  $\mathcal{C}$  has finite  $E$ -projective dimension  $n > 0$ . Then, by Lemma 3.9, there exists some object  $X$  in  $\mathcal{C}$  of  $E$ -projective dimension 1. Choose an  $E$ -projective resolution

$$0 \rightarrow P_1 \xrightarrow{s} P_0 \rightarrow X \rightarrow 0$$

of  $X$ . Then we have the commutative diagram

$$\begin{array}{ccccc} P_1 & \xleftarrow{\text{id}} & P_1 & \xrightarrow{\text{id}} & P_1 \\ \downarrow s & & \downarrow \text{id} & & \downarrow s \\ P_0 & \xleftarrow{s} & P_1 & \xrightarrow{s} & P_0 \end{array}$$

in which all vertical arrows are  $E$ -stable equivalences (since any map between two  $E$ -projective objects is an  $E$ -stable equivalence!) and all horizontal arrows are  $E$ -monomorphisms. We compute the induced map on pushouts by the commutative diagram with exact rows

$$\begin{array}{ccccccc} 0 & \longrightarrow & P_1 & \xrightarrow{\Delta} & P_1 \oplus P_1 & \longrightarrow & P_1 \longrightarrow 0 \\ & & \downarrow \text{id} & & \downarrow s \oplus s & & \downarrow \\ 0 & \longrightarrow & P_1 & \longrightarrow & P_0 \oplus P_0 & \longrightarrow & P_0 \coprod_{P_1} P_0 \longrightarrow 0. \end{array}$$

Exactness of the top row, as well as an isomorphism  $P_0 \coprod_{P_1} P_0 \cong X \oplus P_0$ , both follow from Lemma 3.8. So the pushout map  $P_1 \coprod_{P_1} P_1 \rightarrow P_0 \coprod_{P_1} P_0$  is, up to isomorphism, the map

$P_1 \rightarrow X \oplus P_0$ . Applying  $\text{Ext}_{C/E}^1(-, M)$  to this map, we get

$$\begin{array}{ccc}
 \text{Ext}_{C/E}^1(P_0 \coprod_{P_1} P_0, M) & \longrightarrow & \text{Ext}_{C/E}^1(P_1 \coprod_{P_1} P_1, M) \\
 \downarrow \cong & & \downarrow \cong \\
 \text{Ext}_{C/E}^1(X \oplus P_0, M) & \longrightarrow & \text{Ext}_{C/E}^1(P_1, M) \\
 \downarrow \cong & & \downarrow \cong \\
 \text{Ext}_{C/E}^1(X, M) & \longrightarrow & 0
 \end{array}$$

for all objects  $M$  of  $C$ . Since  $X$  is assumed to be of  $E$ -projective dimension 1, it is not  $E$ -projective, so by Lemma 3.1,  $\text{Ext}_{C/E}^1(X, M)$  is nonzero for some object  $M$  in  $C$ . So by Lemma 3.6, the pushout map  $P_1 \coprod_{P_1} P_1 \rightarrow P_0 \coprod_{P_1} P_0$  is not an  $E$ -stable equivalence.  $\square$

**Corollary 3.12.** *Let  $C$  be a weak Waldhausen abelian category. Let  $E$  be a class allowable for  $C$ . Suppose  $C$  has enough  $E$ -projectives. Then  $C$  is not a Waldhausen category unless each object in  $C$  has  $E$ -projective dimension either 0 or  $\infty$ .*

*Proof.* Well-definedness of homotopy colimits is Waldhausen's axiom **Weq 2** in the definition of a Waldhausen category, from [13].  $\square$

#### 4. POSITIVE RESULTS ON HOMOTOPY PUSHOUTS AND HOMOTOPY COFIBERS.

In this section we prove that homotopy pushouts in a weak Waldhausen abelian category  $C$  are well-defined if one makes some mild assumptions on  $C$ , as well as one quite significant assumption on  $C$ : that every relatively projective object is relatively injective. In the absolute case, i.e., the case where  $E$  is the class of all short exact sequences in  $C$ , this condition is somewhat weaker than the assumption that  $C$  be quasi-Frobenius, which holds when  $C$  is the category of modules over any quasi-Frobenius ring (e.g. connected co-commutative finite-dimensional Hopf algebras over fields, such as finite-dimensional sub-Hopf-algebras of the Steenrod algebra). Recall that an abelian category  $C$  is said to be “quasi-Frobenius” if projective and injective objects coincide in  $C$ .

The following proposition is the relative-homological-algebraic generalization of the main result of Oort's paper [9]. The proof follows Oort's but with some adaptations (which are easy) to the relative situation.

**Proposition 4.1.** *Let  $C$  be an abelian category,  $E$  an allowable class in  $C$  with sectile epics. Suppose  $C$  has enough  $E$ -projectives. Then a map  $f : X \rightarrow Y$  in  $C$  induces a natural isomorphism*

$$\text{Ext}_{C/E}^i(Y, -) \rightarrow \text{Ext}_{C/E}^i(X, -)$$

*if and only if there exists a short exact sequence in  $E$*

$$(4.8) \quad 0 \rightarrow Q \rightarrow P \oplus X \xrightarrow{p} Y \rightarrow 0$$

*with  $P$  an  $E$ -projective and  $Q$  of  $E$ -projective dimension  $\leq i - 1$ , such that the composite  $X \xrightarrow{i} P \oplus X \xrightarrow{p} Y$  is equal to  $f$ . (Here  $i$  is inclusion as the second summand.)*

*Proof.* If short exact sequence 4.8 exists with the described properties, then for any object  $M$  of  $C$ , the induced long exact sequence in  $\text{Ext}_{C/E}$  reads

$$0 \cong \text{Ext}_{C/E}^i(Q, M) \longleftarrow \text{Ext}_{C/E}^i(P \oplus X, M) \longleftarrow \text{Ext}_{C/E}^i(Y, M) \longleftarrow \text{Ext}_{C/E}^{i-1}(Q, M) \cong 0$$

and since  $P$  is projective we now have

$$\mathrm{Ext}_{C/E}^i(Y, M) \cong \mathrm{Ext}_{C/E}^i(P \oplus X, M) \cong \mathrm{Ext}_{C/E}^i(X, M).$$

Now instead assume that  $f$  induces an isomorphism in  $\mathrm{Ext}_{C/E}^i$ . We want to construct a short exact sequence 4.8 with the described properties. Choose exact sequences for  $X, Y$

$$(4.9) \quad \begin{array}{ccccccccccccccc} 0 & \longrightarrow & N & \xrightarrow{d_{i-1}^Q} & Q_{i-2} & \xrightarrow{d_{i-2}^Q} & \dots & \xrightarrow{d_2^Q} & Q_1 & \xrightarrow{d_1^Q} & Q_0 & \xrightarrow{d_0^Q} & X & \longrightarrow & 0 \\ \downarrow & & \downarrow \theta_{i-1} & & \downarrow \theta_{i-2} & & & & \downarrow \theta_1 & & \downarrow \theta_0 & & \downarrow f & & \downarrow \\ 0 & \longrightarrow & M & \xrightarrow{d_{i-1}^P} & P_{i-2} & \xrightarrow{d_{i-2}^P} & \dots & \xrightarrow{d_2^P} & P_1 & \xrightarrow{d_1^P} & P_0^{d_0^P} & \longrightarrow & Y & \longrightarrow & 0 \end{array}$$

with each  $Q_j$  and  $P_j$  an  $E$ -projective, with each short exact sequence

$$0 \rightarrow \mathrm{im} \, d_{j+1}^Q \rightarrow Q_j \rightarrow \mathrm{im} \, d_j^Q \rightarrow 0$$

and

$$0 \rightarrow \mathrm{im} \, d_{j+1}^P \rightarrow P_j \rightarrow \mathrm{im} \, d_j^P \rightarrow 0$$

both in  $E$ , and such that each  $\theta_j$  factors through the kernel of the map  $Q_{j-1} \rightarrow Q_{j-2}$  for  $j \geq 1$ , and  $\theta_0$  factors through the kernel of the map  $Q_0 \rightarrow X$ . Then  $\theta_{n-1}$  induces a natural isomorphism

$$\mathrm{Ext}_{C/E}^1(N, -) \cong \mathrm{Ext}_{C/E}^i(X, -) \cong \mathrm{Ext}_{C/E}^i(Y, -) \cong \mathrm{Ext}_{C/E}^1(M, -)$$

and hence, by Lemma 3.7, there exist  $E$ -projectives  $Q, P$  and an isomorphism  $N \oplus Q \cong M \oplus P$  extending  $\theta_{n-1}$ . We take a direct sum with these  $E$ -projectives to get the commutative diagram with exact rows

$$(4.10) \quad \begin{array}{ccccccccc} 0 \rightarrow N \oplus Q & \longrightarrow & Q_{i-2} \oplus Q & \longrightarrow & Q_{i-3} & \longrightarrow & Q_{i-4} & \longrightarrow & \dots \\ \downarrow \cong & & \downarrow & & \downarrow & & \downarrow & & \\ 0 \rightarrow M \oplus P & \longrightarrow & P_{i-2} \oplus P & \longrightarrow & P_{i-3} & \longrightarrow & P_{i-4} & \longrightarrow & \dots \end{array}$$

and, regarding this as a double complex and totalizing, we get an exact sequence

$$0 \rightarrow Q_{i-2} \oplus Q \rightarrow Q_{i-3} \oplus P_{i-2} \oplus P \rightarrow Q_{i-2} \oplus P_{i-3} \rightarrow Q_{i-4} \oplus P_{i-3} \rightarrow \dots \rightarrow X \oplus P_0 \xrightarrow{p} Y \rightarrow 0$$

which expresses that we have a short exact sequence

$$(4.11) \quad 0 \rightarrow \ker p \rightarrow X \oplus P_0 \xrightarrow{p} Y \rightarrow 0$$

with  $P_0$   $E$ -projective and  $\ker p$  of  $E$ -projective dimension  $\leq i-1$ , and with  $p$  extending  $f$  as desired. All that remains is to check that short exact sequence 4.11 is in  $E$ . This follows from  $p$  being a difference of the map  $f : X \rightarrow Y$  and the  $E$ -projective cover  $d_0^P : P_0 \rightarrow Y$ , as follows: by the dual of Lemma 3.3, the map  $X \oplus P_0 \rightarrow X \oplus Y$  given by the matrix of maps

$$\begin{bmatrix} \mathrm{id}_X & f \\ 0 & p \end{bmatrix}$$

is an  $E$ -epimorphism. By Lemma 3.4, the projection  $X \oplus Y \rightarrow Y$  is an  $E$ -epimorphism as well. So the composite map  $X \oplus P_0 \rightarrow X \oplus Y \rightarrow Y$ , which is equal to  $p$ , is an  $E$ -epimorphism by Lemma 3.5.  $\square$

**Lemma 4.2.** *Let  $C$  be an abelian category and let  $E$  be an allowable class in  $C$  with sectile epics. Suppose  $C$  has enough  $E$ -projectives, and suppose that every  $E$ -projective object is  $E$ -injective. If  $X \rightarrow Y$  is a map in  $C$  which induces a natural isomorphism of functors*

$$(4.12) \quad \text{Ext}_{C/E}^2(Y, -) \xrightarrow{\cong} \text{Ext}_{C/E}^2(X, -),$$

*then  $X \rightarrow Y$  is an  $E$ -stable equivalence.*

*Proof.* Let  $f : X \rightarrow Y$  be a map which induces a natural isomorphism of functors 4.12. Then, by Prop. 4.1, there exists a short exact sequence in  $E$

$$(4.13) \quad 0 \rightarrow Q \rightarrow P \oplus X \rightarrow Y \rightarrow 0$$

where  $P \oplus X \rightarrow Y$  extends  $f$  and both  $P$  and  $Q$  are  $E$ -projective. Now we use the assumption that every  $E$ -projective in  $C$  is  $E$ -injective: since  $Q$  is  $E$ -injective, short exact sequence 4.13 splits, and we get an isomorphism  $P \oplus X \xrightarrow{\cong} Q \oplus Y$ . Now Lemma 3.7 implies that  $f$  induces a natural isomorphism in  $\text{Ext}_{C/E}^1$  and hence, by Lemma 3.6,  $f$  is an  $E$ -stable equivalence.  $\square$

**Lemma 4.3.** *Let  $C$  be a weak Waldhausen abelian category. Let  $E$  be a class allowable for  $C$ . Suppose  $C$  has enough  $E$ -projectives and enough  $E$ -injectives, suppose  $E$  has sectile epics and retractile monics, and suppose every  $E$ -projective object is  $E$ -injective. Then, for any cofibration  $f : X \rightarrow Y$  and any weak equivalence  $g : X \rightarrow Z$  in  $C$ , the pushout map  $Y \rightarrow Y \amalg_X Z$  is also a weak equivalence.*

*Proof.* The given maps fit into a commutative diagram with exact rows in  $E$

$$\begin{array}{ccccccc} 0 & \longrightarrow & X & \xrightarrow{f} & Y & \longrightarrow & \text{coker } f \longrightarrow 0 \\ & & \downarrow g & & \downarrow & & \downarrow \cong \\ 0 & \longrightarrow & Z & \longrightarrow & Y \amalg_X Z & \longrightarrow & \text{coker } f \longrightarrow 0 \end{array}$$

and since  $g$  is an  $E$ -stable equivalence, Lemma 3.6 gives us, for any object  $M$  of  $C$ , the marked isomorphisms in the commutative diagram with exact columns

$$\begin{array}{ccc} \text{Ext}_{C/E}^1(Z, M) & \xrightarrow{\cong} & \text{Ext}_{C/E}^1(X, M) \\ \downarrow & & \downarrow \\ \text{Ext}_{C/E}^2(\text{coker } f, M) & \xrightarrow{\cong} & \text{Ext}_{C/E}^2(\text{coker } f, M) \\ \downarrow & & \downarrow \\ \text{Ext}_{C/E}^2(Y \amalg_X Z, M) & \longrightarrow & \text{Ext}_{C/E}^2(Y, M) \\ \downarrow & & \downarrow \\ \text{Ext}_{C/E}^2(Z, M) & \xrightarrow{\cong} & \text{Ext}_{C/E}^2(X, M) \\ \downarrow & & \downarrow \\ \text{Ext}_{C/E}^3(\text{coker } f, M) & \xrightarrow{\cong} & \text{Ext}_{C/E}^3(\text{coker } f, M). \end{array}$$



So by the Five Lemma,  $Y \rightarrow Y \coprod_X Z$  induces a natural isomorphism of functors

$$\mathrm{Ext}_{C/E}^2(Y \coprod_X Z, -) \xrightarrow{\cong} \mathrm{Ext}_{C/E}^2(Y, -)$$

and hence, by Lemma 4.2,  $Y \rightarrow Y \coprod_X Z$  is an  $E$ -stable equivalence, hence a weak equivalence.  $\square$

**Proposition 4.4.** *Let  $\mathcal{C}$  be a weak Waldhausen abelian category. Let  $E$  be a class allowable for  $\mathcal{C}$ . Suppose  $\mathcal{C}$  has enough  $E$ -projectives and enough  $E$ -injectives, suppose  $E$  has sectile epics and retractile monics, and suppose that every  $E$ -projective object is  $E$ -injective. Then homotopy pushouts are well-defined in  $\mathcal{C}$ .*

*Proof.* Let  $\mathcal{D}$  be the small category indexing pushout diagrams, i.e.,  $\mathcal{D}$  has three objects  $A_0, A_1, A_2$ , maps  $A_0 \rightarrow A_1$  and  $A_0 \rightarrow A_2$ , and no other non-identity maps. Suppose  $F, G : \mathcal{D} \rightarrow \mathcal{C}$  are homotopy colimit diagrams and  $\phi : F \rightarrow G$  is a natural transformation such that  $\phi(X) : F(X) \rightarrow G(X)$  is an  $E$ -stable equivalence for every object  $X$  of  $\mathcal{D}$ . Then we have the commutative diagram with rows short exact sequences in  $E$ :

$$\begin{array}{ccccccccc} 0 & \longrightarrow & F(A_0) & \longrightarrow & F(A_1) \oplus F(A_2) & \longrightarrow & \mathrm{colim} F & \longrightarrow & 0 \\ \downarrow & & \downarrow & & \downarrow & & \downarrow & & \downarrow \\ 0 & \longrightarrow & G(A_0) & \longrightarrow & G(A_1) \oplus G(A_2) & \longrightarrow & \mathrm{colim} G & \longrightarrow & 0. \end{array}$$

That the maps  $F(A_0) \rightarrow F(A_1) \oplus F(A_2)$  and  $G(A_0) \rightarrow G(A_1) \oplus G(A_2)$  are  $E$ -monomorphisms, and hence that the rows are exact and in  $E$ , follows from Lemma 3.3. Now, for any object  $M$  of  $\mathcal{C}$ , we get the commutative diagram with exact columns

$$\begin{array}{ccc} \mathrm{Ext}_{C/E}^1(G(A_1) \oplus G(A_2), M) & \xrightarrow{\cong} & \mathrm{Ext}_{C/E}^1(F(A_1) \oplus F(A_2), M) \\ \downarrow & & \downarrow \\ \mathrm{Ext}_{C/E}^1(G(A_0), M) & \xrightarrow{\cong} & \mathrm{Ext}_{C/E}^1(F(A_0), M) \\ \downarrow & & \downarrow \\ \mathrm{Ext}_{C/E}^2(\mathrm{coker} G, M) & \xrightarrow{\quad} & \mathrm{Ext}_{C/E}^2(\mathrm{coker} F, M) \\ \downarrow & & \downarrow \\ \mathrm{Ext}_{C/E}^2(G(A_1) \oplus G(A_2), M) & \xrightarrow{\cong} & \mathrm{Ext}_{C/E}^2(F(A_1) \oplus F(A_2), M) \\ \downarrow & & \downarrow \\ \mathrm{Ext}_{C/E}^2(G(A_0), M) & \xrightarrow{\cong} & \mathrm{Ext}_{C/E}^2(F(A_0), M) \end{array}$$

where the horizontal maps marked as isomorphisms are isomorphisms by Lemma 3.6. By the Five Lemma, the remaining horizontal map is an isomorphism. So we have a natural isomorphism of functors

$$\mathrm{Ext}_{C/E}^2(\mathrm{colim} G, -) \xrightarrow{\cong} \mathrm{Ext}_{C/E}^2(\mathrm{colim} F, -)$$

and now, by Lemma 4.2, the map  $\mathrm{colim} F \rightarrow \mathrm{colim} G$  is an  $E$ -stable equivalence. Hence homotopy pushouts are well-defined in  $\mathcal{C}$ .  $\square$

**Corollary 4.5.** *Let  $\mathcal{C}$  be a weak Waldhausen abelian category. Let  $E$  be a class allowable for  $\mathcal{C}$ . Suppose  $\mathcal{C}$  has enough  $E$ -projectives and enough  $E$ -injectives, suppose  $E$  has sectile epics and retractile monics, and suppose that every  $E$ -projective object is  $E$ -injective. Then  $\mathcal{C}$  satisfies Waldhausen's axiom **Weq 2**.*

*Proof.* Follows immediately from Lemma 4.3 and Prop. 4.4.  $\square$

## 5. POSITIVE RESULTS ON SEQUENTIAL HOMOTOPY COLIMITS.

In this section we show that, under the same conditions from the previous section (that relatively projective objects are relatively injective), sequential homotopy colimits are well-defined (Prop. 5.2). As a corollary, in the next section we will be able to show that geometric realization of simplicial objects in  $\mathcal{C}$  is well-defined (Cor. 6.8).

**Lemma 5.1.** *Suppose  $\mathcal{C}$  is an abelian category and  $E$  is an allowable class in  $\mathcal{C}$  with retractile monics. Suppose  $\mathcal{C}$  has enough  $E$ -projectives and enough  $E$ -injectives. Suppose we have objects  $P, X, Y$  in  $\mathcal{C}$  with  $P$  an  $E$ -projective, and suppose we have a map  $f : X \rightarrow Y$  and an  $E$ -epimorphism  $p : P \rightarrow X$ . Then there exists an  $E$ -projective object  $Q$ , a split monomorphism  $g : P \rightarrow Q$  with  $E$ -projective cokernel, and an  $E$ -epimorphism  $q : Q \rightarrow Y$  making the diagram*

$$(5.14) \quad \begin{array}{ccc} P & \xrightarrow{p} & X \\ \downarrow g & & \downarrow f \\ Q & \xrightarrow{q} & Y \end{array}$$

*commute.*

*Proof.* Choose an  $E$ -projective  $P_0$  and an  $E$ -epimorphism  $s : P_0 \rightarrow Y$ . Since  $P$  is  $E$ -projective, the composite map  $f \circ p : P \rightarrow Y$  lifts over  $s$  to give a map  $\ell : P \rightarrow P_0$ , i.e.,  $s \circ \ell = f \circ p$ . Let  $g : P \rightarrow P \oplus P_0$  be the map given by the matrix of maps

$$g = \begin{bmatrix} \text{id}_P & \ell \end{bmatrix}$$

and let  $q : P \oplus P_0 \rightarrow Y$  be the map given by the matrix of maps

$$q = \begin{bmatrix} 0 \\ s \end{bmatrix}.$$

It is trivial to check that the diagram

$$(5.15) \quad \begin{array}{ccc} P & \xrightarrow{p} & X \\ \downarrow g & & \downarrow f \\ P \oplus P_0 & \xrightarrow{q} & Y \end{array}$$

commutes. The map  $q$  is an  $E$ -epimorphism since  $s$  is, by the dual of Lemma 3.4 combined with Lemma 3.2. We also have that  $\pi \circ g = \text{id}_P$ , where  $\pi : P \oplus P_0 \rightarrow P$  is projection to the first summand. So  $g$  is a split monomorphism. That its cokernel is  $E$ -projective follows from an easy application of the Nine Lemma to get the commutative diagram with exact

rows and exact columns:

$$\begin{array}{ccccccc}
 & & 0 & \longrightarrow & 0 & \longrightarrow & 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 0 & \longrightarrow & 0 & \longrightarrow & P_0 & \xrightarrow{\text{id}} & P_0 \longrightarrow 0 \\
 & & \downarrow & & \downarrow i & & \downarrow \text{id} \\
 0 & \longrightarrow & P & \xrightarrow{g} & P \oplus P_0 & \xrightarrow{\pi'} & P_0 \longrightarrow 0 \\
 & & \downarrow \text{id} & & \downarrow \pi & & \downarrow \\
 0 & \longrightarrow & P & \xrightarrow{\text{id}} & P & \longrightarrow & 0 \longrightarrow 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 & & 0 & \longrightarrow & 0 & \longrightarrow & 0
 \end{array}$$

where  $i$  is inclusion as the second summand and  $\pi'$  is projection to the second summand. So  $P_0$ , an  $E$ -projective, is the cokernel of  $g$ .

So diagram 5.15 is the desired diagram 5.14.  $\square$

For the next proposition, we use the phrase “sequential colimit” to describe any colimit indexed by the partially-ordered set of the natural numbers regarded as a category, i.e., a colimit with shape

$$\bullet \rightarrow \bullet \rightarrow \bullet \rightarrow \dots$$

We also include, in the next proposition, a requirement that sequential colimits of  $E$ -long exact sequences be  $E$ -long exact. This is a mild assumption; in the absolute case, when  $E$  is the class of all short exact sequences in  $\mathcal{C}$ , this assumption is equivalent to Grothendieck’s axiom AB5. We remind the reader that axiom AB5 on an abelian category  $\mathcal{C}$  stipulates that small colimits exist in  $\mathcal{C}$  and that a sequential colimit of exact sequences in  $\mathcal{C}$  remains exact. This axiom is satisfied, for example, by the category of  $R$ -modules, for any ring  $R$ .

**Proposition 5.2.** *Let  $\mathcal{C}$  be a weak Waldhausen abelian category. Let  $E$  be a class allowable for  $\mathcal{C}$ , and suppose that a sequential colimit of  $E$ -long exact sequences in  $\mathcal{C}$  is  $E$ -long exact. Suppose  $\mathcal{C}$  has enough  $E$ -projectives and enough  $E$ -injectives, suppose  $E$  has retractile monics and sectile epics, and suppose that every  $E$ -projective object is  $E$ -injective. Then sequential homotopy colimits are well-defined in  $\mathcal{C}$ .*

*Proof.* Let  $F, G : \mathbb{N} \rightarrow \mathcal{C}$  be homotopy colimit diagrams and let  $\phi : F \rightarrow G$  be a natural transformation (i.e., map of diagrams) such that  $\phi(n) : F(n) \rightarrow G(n)$  is an  $E$ -stable equivalence for every  $n \in \mathbb{N}$ . In other words, we have a commutative diagram

$$(5.16) \quad \begin{array}{ccccccc}
 F(0) & \longrightarrow & F(1) & \longrightarrow & F(2) & \longrightarrow & \dots \\
 \downarrow & & \downarrow & & \downarrow & & \\
 G(0) & \longrightarrow & G(1) & \longrightarrow & G(2) & \longrightarrow & \dots
 \end{array}$$

in which all horizontal maps are cofibrations (in particular,  $E$ -monomorphisms) and all vertical maps are  $E$ -stable equivalences. Then, by Lemma 3.6, the vertical maps in the

diagram

$$\begin{array}{ccccccc}
 \mathrm{Ext}_{C/E}^n(F(0), M) & \longleftarrow & \mathrm{Ext}_{C/E}^n(F(1), M) & \longleftarrow & \mathrm{Ext}_{C/E}^n(F(2), M) & \longleftarrow & \dots \\
 \uparrow & & \uparrow & & \uparrow & & \\
 \mathrm{Ext}_{C/E}^n(G(0), M) & \longleftarrow & \mathrm{Ext}_{C/E}^n(G(1), M) & \longleftarrow & \mathrm{Ext}_{C/E}^n(G(2), M) & \longleftarrow & \dots
 \end{array}$$

are isomorphisms for all  $n \geq 1$  and for any object  $M$  of  $C$ , and these isomorphisms are natural in  $M$ . Consequently, we have natural isomorphisms

$$(5.17) \quad \lim_i \mathrm{Ext}_{C/E}^n(G(i), M) \xrightarrow{\cong} \lim_i \mathrm{Ext}_{C/E}^n(F(i), M)$$

and

$$(5.18) \quad R^1 \lim_i \mathrm{Ext}_{C/E}^n(G(i), M) \xrightarrow{\cong} R^1 \lim_i \mathrm{Ext}_{C/E}^n(F(i), M)$$

for all  $n \geq 1$ , where we are writing  $R^1 \lim$  for the first right-derived functor of  $\lim$ .

Now we can use Lemma 5.1 to choose  $E$ -projective resolutions for each  $F(i)$  to get a commutative diagram

$$\begin{array}{ccccccccc}
 \dots & \longrightarrow & P_{2,0}^F & \longrightarrow & P_{1,0}^F & \longrightarrow & P_{0,0}^F & \longrightarrow & F(0) & \longrightarrow & 0 \\
 & & \downarrow & & \downarrow & & \downarrow & & \downarrow & & \downarrow \\
 \dots & \longrightarrow & P_{2,1}^F & \longrightarrow & P_{1,1}^F & \longrightarrow & P_{0,1}^F & \longrightarrow & F(1) & \longrightarrow & 0 \\
 & & \downarrow & & \downarrow & & \downarrow & & \downarrow & & \downarrow \\
 \dots & \longrightarrow & P_{2,2}^F & \longrightarrow & P_{1,2}^F & \longrightarrow & P_{0,2}^F & \longrightarrow & F(2) & \longrightarrow & 0 \\
 & & \downarrow & & \downarrow & & \downarrow & & \downarrow & & \downarrow \\
 & & \vdots & & \vdots & & \vdots & & \vdots & & \vdots
 \end{array}$$

in which each row is an  $E$ -projective resolution and each vertical map  $P_{i,j}^F \rightarrow P_{i,j+1}^F$  is a split monomorphism.

We claim that, for every  $i \in \mathbb{N}$ , the colimit  $\mathrm{colim}_j P_{i,j}^F$  is  $E$ -projective. Let  $f : X \rightarrow Y$  be an  $E$ -epimorphism and  $g : \mathrm{colim}_j P_{i,j}^F \rightarrow Y$  be a map. We write  $g_j : P_{i,j}^F \rightarrow Y$  for the  $j$ th component map of  $g$ . Since  $P_{i,0}^F$  is  $E$ -projective, there exists a lift  $\ell_0 : P_{i,0}^F \rightarrow X$  of  $g_0$  over  $f$ , which provides the first step of an induction. Suppose we have a map  $\ell_j : P_{i,j}^F \rightarrow X$  such that  $f \circ \ell_j = g_j$ . Then, since the map  $P_{i,j}^F \rightarrow P_{i,j+1}^F$  is a split monomorphism with  $E$ -projective cokernel, there exists a map  $\ell_{j+1} : P_{i,j+1}^F \rightarrow X$  making the diagram

$$\begin{array}{ccc}
 F(i) & \longrightarrow & F(i+1) \\
 \downarrow \ell_i & \nearrow \ell_{i+1} & \downarrow g_{i+1} \\
 X & \xrightarrow{f} & Y
 \end{array}$$

commute. So we can assemble the maps  $\{\ell_j\}_{j \in \mathbb{N}}$  into a map  $\ell : \mathrm{colim}_j P_{i,j}^F \rightarrow X$  such that  $f \circ \ell = g$ . So  $\mathrm{colim}_j P_{i,j}^F$  has the universal property defining an  $E$ -projective object, so  $\mathrm{colim}_j P_{i,j}^F$  is  $E$ -projective. We make the same constructions for  $G$  as well as  $F$ , writing  $P_{i,j}^G$  rather than  $P_{i,j}^F$  for the  $E$ -projectives constructed in this way.

Now the chain complex

$$(5.19) \quad \cdots \rightarrow \operatorname{colim}_j P_{2,j}^F \rightarrow \operatorname{colim}_j P_{1,j}^F \rightarrow \operatorname{colim}_j P_{0,j}^F \rightarrow \operatorname{colim} F \rightarrow 0$$

is  $E$ -long exact, due to our assumption that sequential colimits of  $E$ -long exact sequences in  $\mathcal{C}$  are  $E$ -long exact. Furthermore, we have shown that each  $\operatorname{colim}_j P_{i,j}^F$  is  $E$ -projective. So long exact sequence 5.19 is an  $E$ -projective resolution of  $\operatorname{colim} F$ . So, for any object  $M$  of  $\mathcal{C}$ , the cohomology of the cochain complex

$$(5.20) \quad \begin{array}{ccccccc} \cdots & \longleftarrow & \operatorname{hom}_{\mathcal{C}}(\operatorname{colim}_j P_{1,j}^F, M) & \longleftarrow & \operatorname{hom}_{\mathcal{C}}(\operatorname{colim}_j P_{0,j}^F, M) & \longleftarrow & 0 \\ & & \downarrow \cong & & \downarrow \cong & & \downarrow \\ \cdots & \longleftarrow & \lim_j \operatorname{hom}_{\mathcal{C}}(P_{1,j}^F, M) & \longleftarrow & \lim_j \operatorname{hom}_{\mathcal{C}}(P_{0,j}^F, M) & \longleftarrow & 0 \end{array}$$

is  $\operatorname{Ext}_{\mathcal{C}/E}^*(\operatorname{colim} F, M)$ , and this isomorphism is natural in  $M$ .

Now we have the usual short exact sequence relating the cohomology of a sequential limit of cochain complexes of abelian groups to the sequential limit of their cohomologies:

$$0 \rightarrow R^1 \lim_j H^{n-1} \operatorname{hom}_{\mathcal{C}}(P_{\bullet,j}^F, M) \rightarrow H^n \lim_j \operatorname{hom}_{\mathcal{C}}(P_{\bullet,j}^F, M) \rightarrow \lim_j H^n \operatorname{hom}_{\mathcal{C}}(P_{\bullet,j}^F, M) \rightarrow 0.$$

Due to isomorphisms 5.17 and 5.18, we now have the commutative diagram with exact rows:

$$\begin{array}{ccccccccc} 0 & \longrightarrow & R^1 \lim_j \operatorname{Ext}_{\mathcal{C}/E}^{n-1}(G(j), M) & \longrightarrow & \operatorname{Ext}_{\mathcal{C}/E}^n(\operatorname{colim} G, M) & \longrightarrow & \lim_j \operatorname{Ext}_{\mathcal{C}/E}^n(G(j), M) & \longrightarrow & 0 \\ \downarrow & & \downarrow \cong & & \downarrow \cong & & \downarrow \cong & & \downarrow \\ 0 & \longrightarrow & R^1 \lim_j H^{n-1} \operatorname{hom}_{\mathcal{C}}(P_{\bullet,j}^G, M) & \longrightarrow & H^n \lim_j \operatorname{hom}_{\mathcal{C}}(P_{\bullet,j}^G, M) & \longrightarrow & \lim_j H^n \operatorname{hom}_{\mathcal{C}}(P_{\bullet,j}^G, M) & \longrightarrow & 0 \\ \downarrow & & \downarrow b & & \downarrow a & & \downarrow c & & \downarrow \\ 0 & \longrightarrow & R^1 \lim_j H^{n-1} \operatorname{hom}_{\mathcal{C}}(P_{\bullet,j}^F, M) & \longrightarrow & H^n \lim_j \operatorname{hom}_{\mathcal{C}}(P_{\bullet,j}^F, M) & \longrightarrow & \lim_j H^n \operatorname{hom}_{\mathcal{C}}(P_{\bullet,j}^F, M) & \longrightarrow & 0 \\ \downarrow & & \downarrow \cong & & \downarrow \cong & & \downarrow \cong & & \downarrow \\ 0 & \longrightarrow & R^1 \lim_j \operatorname{Ext}_{\mathcal{C}/E}^{n-1}(F(j), M) & \longrightarrow & \operatorname{Ext}_{\mathcal{C}/E}^n(\operatorname{colim} F, M) & \longrightarrow & \lim_j \operatorname{Ext}_{\mathcal{C}/E}^n(F(j), M) & \longrightarrow & 0 \end{array}$$

and the vertical map marked  $b$  is an isomorphism if  $n \geq 2$ , and the vertical map marked  $c$  is an isomorphism if  $n \geq 1$ . Hence, by the Five Lemma, the vertical map marked  $a$  is an isomorphism if  $n \geq 2$ .

We conclude that the map

$$\operatorname{Ext}_{\mathcal{C}/E}^n(\operatorname{colim} G, M) \rightarrow \operatorname{Ext}_{\mathcal{C}/E}^n(\operatorname{colim} F, M)$$

is an isomorphism if  $n \geq 2$ . Hence, by Lemma 4.2, the assumption that every  $E$ -projective is  $E$ -injective implies that the map  $\operatorname{colim} F \rightarrow \operatorname{colim} G$  is an  $E$ -stable equivalence. So sequential homotopy colimits in  $\mathcal{C}$  are unique up to homotopy.  $\square$

## 6. POSITIVE RESULTS ON GEOMETRIC REALIZATION.

In this section we prove that, under the same assumptions made in the previous section plus the assumption that our abelian category satisfies Grothendieck's axiom AB3, geometric realization of simplicial objects is well-defined (Cor. 6.8).

One can approach geometric realization as a particular kind of colimit called a “co-end”; this approach is taken in e.g. [7]. We take a different approach to geometric realization

in this section, by regarding geometric realization as the sequential colimit of a certain sequence of homotopy cofibers. We give an abbreviated description of this approach in Def. 6.5, but it is well-known in the special case of a pointed (e.g. stable) model category, and, for example, it appears in the context of a triangulated category in [1].

**Lemma 6.1.** *A pullback of a surjective map of abelian groups is surjective.*

*Proof.* The forgetful functor from abelian groups to sets is a right adjoint, hence preserves limits. It also clearly preserves surjections. So the lemma is true if a pullback of a surjective maps of sets is surjective, which is an elementary exercise.  $\square$

**Lemma 6.2.** *Let  $\mathcal{C}$  be an abelian category and let  $E$  be an allowable class with retractile monics. Then  $E$ -monics are closed under pushout in  $\mathcal{C}$ . That is, if  $X \rightarrow Z$  is an  $E$ -monic and  $X \rightarrow Y$  is any morphism in  $\mathcal{C}$ , then the canonical map  $Y \rightarrow Y \amalg_X Z$  is an  $E$ -monic.*

*Proof.* Suppose  $f : X \rightarrow Z$  is an  $E$ -monic and  $X \rightarrow Y$  any morphism. We have the commutative diagram with exact rows

$$\begin{array}{ccccccc} 0 & \longrightarrow & X & \xrightarrow{f} & Z & \longrightarrow & \operatorname{coker} f \longrightarrow 0 \\ & & \downarrow & & \downarrow & & \downarrow \\ & & Y & \longrightarrow & Y \amalg_X Z & \longrightarrow & \operatorname{coker} f \longrightarrow 0 \end{array}$$

and hence, for every  $E$ -injective  $I$ , the induced commutative diagram of abelian groups

$$\begin{array}{ccccccc} 0 & \longrightarrow & \operatorname{hom}_{\mathcal{C}}(\operatorname{coker} f, I) & \longrightarrow & \operatorname{hom}_{\mathcal{C}}(Z, I) & \longrightarrow & \operatorname{hom}_{\mathcal{C}}(X, I) \longrightarrow 0 \\ & & \uparrow \cong & & \uparrow & & \uparrow \\ 0 & \longrightarrow & \operatorname{hom}_{\mathcal{C}}(\operatorname{coker} f, I) & \longrightarrow & \operatorname{hom}_{\mathcal{C}}(Y \amalg_X Z, I) & \longrightarrow & \operatorname{hom}_{\mathcal{C}}(Y, I). \end{array}$$

Exactness of the top row follows from  $f$  being an  $E$ -monic together with  $E$  having retractile monics, hence  $E$  is its own retractile closure, hence  $E$ -monics are precisely the maps which induce a surjection after applying  $\operatorname{hom}_{\mathcal{C}}(-, I)$  for every  $E$ -injective  $I$ . Now in particular we have a commutative square in the above commutative diagram:

$$\begin{array}{ccc} \operatorname{hom}_{\mathcal{C}}(Z, I) & \longrightarrow & \operatorname{hom}_{\mathcal{C}}(X, I) \\ \uparrow & & \uparrow \\ \operatorname{hom}_{\mathcal{C}}(Y \amalg_X Z, I) & \longrightarrow & \operatorname{hom}_{\mathcal{C}}(Y, I), \end{array}$$

which is a pullback square of abelian groups, by the universal property of the pushout. The top map in the square is a surjection, hence so is the bottom map, Lemma 6.1. So  $\operatorname{hom}_{\mathcal{C}}(Y \amalg_X Z, I) \rightarrow \operatorname{hom}_{\mathcal{C}}(Y, I)$  is a surjection for every  $E$ -injective  $I$ . Again since  $E$  is its own retractile closure, this implies that  $Y \rightarrow Y \amalg_X Z$  is an  $E$ -monic.  $\square$

We now define a weak form of the quasi-Frobenius condition that will allow us to factor maps into cofibrations followed by weak equivalences:

**Definition 6.3.** *Suppose  $\mathcal{C}$  is a weak Waldhausen abelian category and  $E$  a class allowable for  $\mathcal{C}$ . We say that  $\mathcal{C}$  is cone-Frobenius if there exists a functor  $J : \mathcal{C} \rightarrow \mathcal{C}$  and a natural transformation  $\eta : \operatorname{id}_{\mathcal{C}} \rightarrow J$  such that:*

- (1)  $J(X)$  is  $E$ -projective for every object  $X$  of  $\mathcal{C}$ ,
- (2)  $\eta(X) : X \rightarrow J(X)$  is an  $E$ -monomorphism for every object  $X$  of  $\mathcal{C}$ , and
- (3) if  $f : X \rightarrow Y$  is an  $E$ -monomorphism then so is  $J(f) : J(X) \rightarrow J(Y)$ .

We sometimes call the pair  $J, \eta$  a cone functor on  $\mathcal{C}$ .

Here is an example of a cone functor: suppose  $R$  is a Noetherian ring, and let  $U$  be the injective envelope of the direct sum  $\bigoplus R/I$ , where  $I$  ranges across all right ideals of  $R$ . For each right  $R$ -module  $M$ , let

$$J(M) = \prod_{\text{hom}_R(M, U)} U,$$

and let  $\eta(M) : M \rightarrow J(M)$  send  $m$  to the map whose component in the factor corresponding to  $f \in \text{hom}_R(M, U)$  is  $f(m)$ . This gives a functorial embedding of every  $R$ -module into an injective  $R$ -module, and (due to the characterizing property of an injective envelope)  $J$  sends monomorphisms to monomorphisms (this construction is due to Bass, and appears in Ex. 5.26 in Lam's book [5]). If every injective  $R$ -module is projective, then  $J$  is a cone functor. So the category of modules over any Noetherian quasi-Frobenius ring is cone-Frobenius, for example. Similarly, the category of finitely-generated modules over any finite-dimensional quasi-Frobenius algebra over a finite field is also cone-Frobenius.

Now we will begin assuming our weak Waldhausen abelian category  $\mathcal{C}$  is cone-Frobenius. The notation we will usually use is this: for any object  $X$  of  $\mathcal{C}$ , we will write  $i_X : X \rightarrow P_X$  for the chosen  $E$ -monomorphism from  $X$  to an  $E$ -projective  $P_X$ .

The following lemma gives us conditions under which a homotopy pushout can be computed as the pushout of a diagram in which only *one* map is a cofibration, rather than both maps.

**Lemma 6.4.** *Let  $\mathcal{C}$  be a cone-Frobenius weak Waldhausen abelian category. Let  $E$  be a class allowable for  $\mathcal{C}$ . Suppose  $\mathcal{C}$  has enough  $E$ -projectives and enough  $E$ -injectives, suppose  $E$  has sectile epics and retractile monics, suppose every  $E$ -projective object is  $E$ -injective. Then any map  $f : X \rightarrow Y$  can be factored as a composite*

$$(6.21) \quad X \xrightarrow{f_0} \tilde{Y} \xrightarrow{f_1} Y,$$

where  $f_0$  is a cofibration and  $f_1$  is a weak equivalence, and furthermore, the pushout of the diagram

$$(6.22) \quad \begin{array}{ccc} X & \xrightarrow{f_0} & \tilde{Y} \\ \downarrow i_X & & \\ P_X & & \end{array}$$

is weakly equivalent to the pushout of the diagram

$$(6.23) \quad \begin{array}{ccc} X & \xrightarrow{f} & Y \\ \downarrow i_X & & \\ P_X & & \end{array}$$

*Proof.* We let  $\tilde{Y}$  be  $P_X \oplus Y$ , we let  $f_0$  be given by the matrix of maps

$$f_0 = \begin{bmatrix} i_X & f \end{bmatrix},$$

and we let  $f_1$  be the projection to the second summand. It is trivial to check that  $f = f_1 \circ f_0$ . That  $f_1$  is a weak equivalence follows from its being a split epimorphism with  $E$ -projective kernel. That  $f_0$  is a cofibration follows from its being the composite of the inclusion in

the first summand  $X \rightarrow X \oplus Y$  (which is an  $E$ -monomorphism, hence cofibration, by Lemma 3.4) followed by the map  $X \oplus Y \rightarrow P_X \oplus Y$  given by the matrix of maps

$$\begin{bmatrix} i_X & f \\ 0 & \text{id}_Y \end{bmatrix},$$

which is an  $E$ -monomorphism, hence cofibration, by Lemma 3.3. So  $f_0$  is a composite of two cofibrations, hence itself a cofibration. So we have the desired factorization 6.21.

Now we have the commutative diagram

$$(6.24) \quad \begin{array}{ccccc} X & \xrightarrow{f_0} & P_X \oplus Y & \xrightarrow{f_1} & Y \\ \downarrow i_X & & \downarrow & & \downarrow \\ P_X & \longrightarrow & P_X \coprod_X (P_X \oplus Y) & \longrightarrow & (P_X \coprod_X (P_X \oplus Y)) \coprod_{P_X \oplus Y} Y \end{array}$$

in which the two squares are pushout squares, hence the outer rectangle is a pushout diagram, i.e., we have a natural isomorphism

$$\left( P_X \coprod_X (P_X \oplus Y) \right) \coprod_{P_X \oplus Y} Y \cong P_X \coprod_X Y.$$

In diagram 6.24, the maps  $i_X$  and  $f_0$  are cofibrations, hence the central vertical map is as well, by Lemma 6.2. Hence the bottom map

$$P_X \coprod_X (P_X \oplus Y) \rightarrow P_X \coprod_X Y$$

is a pushout of a weak equivalence ( $f_1$ ) along a cofibration (the central vertical map), hence itself a weak equivalence by Lemma 4.3. So we have a weak equivalence, as desired, between the pushout of the diagram 6.22 and the pushout of diagram 6.23.  $\square$

Recall that an abelian category satisfies Grothendieck's axiom AB3 if it has arbitrary (small) colimits. Since any abelian category has coequalizers, axiom AB3 is equivalent to having arbitrary (small) coproducts.

**Definition 6.5.** Suppose  $C$  is a cone-Frobenius weak Waldhausen abelian category satisfying Grothendieck's axiom AB3 as well as the assumptions of Lemma 6.4. Let  $F : \Delta^{\text{op}} \rightarrow C$  be a simplicial object in  $C$ . We will write  $F_n$  for the  $n$ th object of  $F$  and

$$d_i : F_n \rightarrow F_{n-1},$$

$i = 0, \dots, n$ , for the face maps of  $F$ . We write  $\Sigma X$  for the pushout of the diagram

$$\begin{array}{ccc} X & \xrightarrow{i_X} & P_X \\ \downarrow i_X & & \\ P_X & & \end{array}$$

Then by a geometric realization tower of  $F$  we mean the diagram  $GR_F : \mathbb{N} \rightarrow C$  defined inductively as follows:

$$GR_F(0) = F_0 \oplus \coprod_{n>0} P_{F_n},$$



and if  $GR_F(i)$  has already been defined for  $i = 0, \dots, n-1$ , we define  $GR_F(n)$  as the pushout in the diagram

$$(6.25) \quad \begin{array}{ccc} \Sigma^{n-1}(F_n \oplus \coprod_{i>n} P_{F_i}) & \xrightarrow{f_n} & GR_F(n-1) \\ \downarrow \Sigma^{n-1}(i_{F_n} \oplus \text{id}) & & \downarrow g_n \\ \Sigma^{n-1}(\coprod_{i \geq n} P_{F_i}) & \longrightarrow & GR_F(n) \end{array}$$

where  $f_n : \Sigma^{n-1}(F_n \oplus \coprod_{i>n} P_{F_i}) \rightarrow GR_F(n-1)$  is the map obtained from the two nulhomotopies (i.e., factorizations through an  $E$ -projective) of the composite map

$$\Sigma^{n-2}(F_n \oplus \coprod_{i>n} P_{F_i}) \xrightarrow{\Sigma^{n-2}d} \Sigma^{n-2}(F_{n-1} \oplus \coprod_{i>n-1} P_{F_i}) \xrightarrow{f_{n-1}} GR_F(n-2) \xrightarrow{g_{n-1}} GR_F(n-1),$$

where we write

$$d : F_n \oplus \coprod_{i>n} P_{F_i} \rightarrow F_{n-1} \oplus \coprod_{i>n-1} P_{F_i}$$

for the map given on the summands  $F_n, P_{F_{n+1}}, P_{F_{n+2}}, \dots$  of its domain as follows:

- on the summand  $F_n$  of its domain, it is the alternating sum

$$d_0 - d_1 + d_2 - \dots + (-1)^{n-1} d_{n-1} : F_n \rightarrow F_{n-1}$$

plus the map  $i_{F_n} : F_n \rightarrow P_{F_n}$ ,

- and on each summand  $P_{F_i}$  for  $i > n$ , it is simply the inclusion of the summand  $P_{F_i}$  into the codomain.

Finally, by the geometric realization of  $F$  we mean the colimit  $\text{colim } GR_F$  of the geometric realization tower of  $F$ .

Here is a simple way of describing the maps  $d : F_n \oplus \coprod_{i>n} P_{F_i} \rightarrow F_{n-1} \oplus \coprod_{i>n-1} P_{F_i}$  appearing in Def. 6.5: if one applies the factorization 6.21 from Lemma 6.4 to the alternating sum map  $d_0 - d_1 + d_2 - \dots + (-1)^{n-1} d_{n-1} : F_n \rightarrow F_{n-1}$ , one gets a cofibration  $f_0 : F_n \rightarrow F_{n-1} \oplus P_{F_n}$ . The map  $d$  is simply the direct sum of  $f_0$  with the identity map on all the  $E$ -projectives  $P_{F_i}$  that will appear later on in the geometric realization tower. Note that, if  $P$  is  $E$ -projective, then so is  $\Sigma P$ , since the assumptions made in Def. 6.5 imply that homotopy pushouts are well-defined in  $\mathcal{C}$  due to Prop. 4.4, which in turn implies that a homotopy pushout of  $E$ -projective objects is  $E$ -projective, by Prop. 3.10. Furthermore, the cone-Frobenius assumption implies that  $i_{F_n}$  being a cofibration forces  $\Sigma i_{F_n}$  to be a cofibration. So the left-hand vertical map in square 6.25 really is an  $E$ -monomorphism into an  $E$ -projective object. So by Lemma 6.4, square 6.25 is computing a homotopy pushout.

**Lemma 6.6.** *Under the assumptions made in Def. 6.5, making different choices of the cone functor; in particular the  $E$ -projective objects  $P_X$  and cofibrations  $i_X$ , does not change the  $E$ -stable equivalence type of each object  $GR_F(n)$  in the geometric realization tower.*

*Proof.* Suppose we have two choices  $P_X, P'_X$  of  $E$ -projective object and two choices of cofibration,  $i_X : X \rightarrow P_X$  and  $i'_X : X \rightarrow P'_X$ . For any cofibration  $f : X \rightarrow Y$ , we have the two pushout diagrams

$$\begin{array}{ccc} X & \xrightarrow{i_X} & P_X \\ \downarrow f & & \downarrow f \\ Y & & Y \end{array} \quad \text{and} \quad \begin{array}{ccc} X & \xrightarrow{i'_X} & P'_X \\ \downarrow f & & \downarrow f \\ Y & & Y \end{array}.$$

By Lemma 6.4, the pushout of each diagram is  $E$ -stably equivalent to the pushout of the diagram

$$\begin{array}{ccc} X & \longrightarrow & 0 \\ \downarrow f & & \\ Y & & \end{array}$$

So the  $E$ -stable equivalence type of the homotopy cofiber of a cofibration doesn't depend on the choice of  $i_X, P_X$ .

Now we handle the dependence of the factorization 6.21 on the choices of  $i_X, P_X$ . We have the two pushout diagrams

$$(6.26) \quad \begin{array}{ccc} X & \xrightarrow{i_X} & P_X \\ \downarrow f_0 & & \\ P_X \oplus Y & & \end{array} \quad \text{and} \quad \begin{array}{ccc} X & \xrightarrow{i'_X} & P'_X \\ \downarrow f'_0 & & \\ P'_X \oplus Y & & \end{array}$$

arising from factorization 6.21, and we want to know that the pushouts of these two diagrams are  $E$ -stably equivalent. We accomplish this with the pushout diagram

$$(6.27) \quad \begin{array}{ccc} X & \xrightarrow{i_X} & P_X \\ \downarrow m & & \\ P_X \oplus P'_X \oplus Y & & \end{array}$$

where  $m$  is given the matrix of maps

$$m = \begin{bmatrix} i_X & i'_X & f \end{bmatrix},$$

and is a cofibration by Lemma 3.3. We note that diagram 6.27 maps to each of the two diagrams 6.26; we handle the map to the left-hand diagram 6.26, and the map to the right-hand diagram is handled similarly. Since  $i_X, f_0$ , and  $m$  are all cofibrations, Lemma 6.2 implies that, in the pushout square

$$\begin{array}{ccc} P_X \oplus P'_X \oplus Y & \longrightarrow & P_X \coprod_X (P_X \oplus P'_X \oplus Y) \\ \downarrow & & \downarrow \\ P_X \oplus Y & \longrightarrow & P_X \coprod_X (P_X \oplus Y), \end{array}$$

the top horizontal map is a cofibration. The left-hand vertical map is a weak equivalence, since it is a split epimorphism with  $E$ -projective kernel; so by Lemma 4.3, the right-hand vertical map is also a weak equivalence. A similar argument holds for the right-hand pushout diagram 6.26, so since the pushouts of the two pushout diagrams in 6.26 are each  $E$ -stably equivalent to the pushout of diagram 6.27, the two pushout diagrams in 6.26 are  $E$ -stably equivalent to one another. So the choice of  $i_X, P_X$  used in the construction of the factorization 6.21 doesn't affect the  $E$ -stable equivalence type of the resulting homotopy pushouts.

Finally, since  $GR_F$  is constructed entirely from these two operations (factorizations as in 6.21 and homotopy cofibers of cofibrations), up to levelwise  $E$ -stable equivalence,  $GR_F$  does not depend on the choices of  $i_X, P_X$ .  $\square$

**Proposition 6.7.** *Let  $\mathcal{C}$  be a cone-Frobenius weak Waldhausen abelian category. Let  $E$  be a class allowable for  $\mathcal{C}$ . Suppose  $\mathcal{C}$  has enough  $E$ -projectives and enough  $E$ -injectives, suppose  $E$  has sectile epics and retractile monics, suppose every  $E$ -projective object is  $E$ -injective. Then, for any simplicial object  $F : \Delta^{\text{op}} \rightarrow \mathcal{C}$  in  $\mathcal{C}$ , the geometric realization tower  $GR_F : \mathbb{N} \rightarrow \mathcal{C}$  is a homotopy colimit diagram. Furthermore, if  $F, G : \Delta^{\text{op}} \rightarrow \mathcal{C}$  are two simplicial objects and  $\phi : F \rightarrow G$  a levelwise weak equivalence, then the induced natural transformation  $GR_\phi : GR_F \rightarrow GR_G$  has the property that, for every natural number  $n$ , the map  $GR_\phi(n) : GR_F(n) \rightarrow GR_G(n)$  is a weak equivalence.*

*Proof.* First we check that  $GR_F$  is a homotopy pushout diagram. All we need to check is that, for every natural number  $n$ , the map  $GR_F(n) \rightarrow GR_F(n+1)$  is a cofibration. But this map is the pushout of diagram 6.25, which is the pushout of a cofibration along a cofibration, hence itself a cofibration by Lemma 6.2.

Now suppose  $F, G, \phi$  are as in the statement of the proposition. The maps  $GR_\phi(n) : GR_F(n) \rightarrow GR_G(n)$  are, by construction, pushouts of weak equivalences along cofibrations, hence by Lemma 4.3, they are themselves weak equivalences.  $\square$

**Corollary 6.8.** *Let  $\mathcal{C}, E$  be as in Def. 6.5, and suppose that a sequential colimit of  $E$ -long exact sequences in  $\mathcal{C}$  is  $E$ -long exact. Then geometric realization of simplicial objects in  $\mathcal{C}$  is well defined. That is, if we have two simplicial objects  $F, G : \Delta^{\text{op}} \rightarrow \mathcal{C}$  in  $\mathcal{C}$  and a natural transformation  $\phi : F \rightarrow G$  such that  $\phi(n) : F(n) \rightarrow G(n)$  is a weak equivalence for every natural number  $n$ , then the induced map of geometric realizations  $\text{colim } GR_F \rightarrow \text{colim } GR_G$  is a weak equivalence.*

*Proof.* By Prop. 6.7,  $\phi$  induces a natural transformation  $GR_\phi : GR_F \rightarrow GR_G$  of homotopy colimit diagrams which is a levelwise weak equivalence. Then by Prop. 5.2,  $GR_\phi$  induces a weak equivalence of colimits  $\text{colim } GR_F \rightarrow \text{colim } GR_G$ .  $\square$

## 7. APPENDIX ON BASIC NOTIONS OF RELATIVE HOMOLOGICAL ALGEBRA.

Here is an appendix on some ideas in relative homological algebra. Since this subject is a little bit obscure, some readers might find the definitions (which are all classical, except for Def. 7.6) in this appendix helpful.

**Definition 7.1.** *An allowable class in  $\mathcal{C}$  consists of a collection  $E$  of short exact sequences in  $\mathcal{C}$  which is closed under isomorphism of short exact sequences and which contains every short exact sequence in which at least one object is the zero object of  $\mathcal{C}$ . (See section IX.4 of [6] for this definition and basic properties.)*

The usual “absolute” homological algebra in an abelian category  $\mathcal{C}$  is recovered by letting the allowable class  $E$  consist of *all* short exact sequences in  $\mathcal{C}$ .

Once one chooses an allowable class  $E$ , one has the notion of monomorphisms relative to  $E$ , or “ $E$ -monomorphisms,” and epimorphisms relative to  $E$ , or “ $E$ -epimorphisms.”

**Definition 7.2.** *Let  $E$  be an allowable class in  $\mathcal{C}$ . A monomorphism  $f : M \rightarrow N$  in  $\mathcal{C}$  is called an  $E$ -monomorphism or an  $E$ -monic if the short exact sequence*

$$0 \rightarrow M \xrightarrow{f} N \rightarrow \text{coker } f \rightarrow 0$$

*is in  $E$ .*

*Dually, an epimorphism  $g : M \rightarrow N$  is called an  $E$ -epimorphism or an  $E$ -epic if the short exact sequence*

$$0 \rightarrow \ker f \rightarrow M \xrightarrow{f} N \rightarrow 0$$

is in  $E$ .

In the absolute case, the case that  $E$  is all short exact sequences in  $C$ , the  $E$ -monomorphisms are simply the monomorphisms, and the  $E$ -epimorphisms are simply the epimorphisms.

Projective and injective objects are at the heart of homological algebra. In relative homological algebra, one has the notion of relative projectives, or  $E$ -projectives: these are simply the objects which lift over every  $E$ -epimorphism. The  $E$ -injectives are defined dually.

**Definition 7.3.** Let  $E$  be an allowable class in  $C$ . An object  $X$  of  $C$  is said to be an  $E$ -projective if, for every diagram

$$\begin{array}{ccc} & & X \\ & & \downarrow \\ M & \xrightarrow{f} & N \end{array}$$

in which  $f$  is an  $E$ -epic, there exists a morphism  $X \rightarrow M$  making the above diagram commute.

Dually, an object  $X$  of  $C$  is said to be an  $E$ -injective if, for every diagram

$$\begin{array}{ccc} M & \xrightarrow{f} & N \\ \downarrow & & \\ & & X \end{array}$$

in which  $f$  is an  $E$ -monic, there exists a morphism  $N \rightarrow X$  making the above diagram commute.

When the allowable class  $E$  is clear from context we sometimes refer to  $E$ -projectives and  $E$ -injectives as relative projectives and relative injectives, respectively.

In the absolute case, the case that  $E$  is all short exact sequences in  $C$ , the  $E$ -projectives are simply the projectives, and the  $E$ -injectives are simply the injectives.

Once one has a notion of relative projectives, one has a reasonable notion of a stable equivalence or, loosely, a “homotopy” between maps, as studied (usually in the absolute case, where  $E$ -projectives are simply projectives) in stable representation theory:

**Definition 7.4.** Let  $E$  be an allowable class in  $C$ . Let  $f, g : M \rightarrow N$  be morphisms in  $C$ . We say that  $f$  and  $g$  are  $E$ -stably equivalent and we write  $f \simeq g$  if  $f - g$  factors through an  $E$ -projective object of  $C$ .

One then has the notion of stable equivalence of objects, or loosely, “homotopy equivalence”:

**Definition 7.5.** We say that a map  $f : M \rightarrow N$  is a  $E$ -stable equivalence if there exists a map  $h : N \rightarrow M$  such that  $f \circ h \simeq \text{id}_N$  and  $h \circ f \simeq \text{id}_M$ .

In the absolute case where  $E$  consists of all short exact sequences in  $C$ , this is the usual notion of stable equivalence of modules over a ring. Over a Hopf algebra over a field, stably equivalent modules have isomorphic cohomology in positive degrees, so if one is serious about computing the cohomology of all finitely-generated modules over a particular Hopf algebra—such as the Steenrod algebra or the group ring of a Morava stabilizer group—it is natural to first compute the representation ring modulo stable equivalence.

Here is a new definition which makes many arguments involving allowable classes substantially smoother:

**Definition 7.6.** *An allowable class  $E$  is said to have retractile monics if, whenever  $g \circ f$  is an  $E$ -monic,  $f$  is also an  $E$ -monic.*

*Dually, an allowable class  $E$  is said to have sectile epics if, whenever  $g \circ f$  is an  $E$ -epic,  $g$  is also an  $E$ -epic.*

The utility of the notion of “having sectile epics” comes from the following fundamental theorem of relative homological algebra, due to Heller (see [6]), whose statement is slightly cleaner is one is willing to use the phrase “having sectile epics.” The consequence of Heller’s theorem is that, in order to specify a “reasonable” allowable class in an abelian category, it suffices to specify the relative projective objects associated to it.

**Theorem 7.7. (Heller.)** *If  $C$  is an abelian category and  $E$  is an allowable class in  $C$  with sectile epics and enough  $E$ -projectives, then an epimorphism  $M \rightarrow N$  in  $C$  is an  $E$ -epic if and only if the induced map  $\text{hom}_C(P, M) \rightarrow \text{hom}_C(P, N)$  of abelian groups is an epimorphism for all  $E$ -projectives  $P$ .*

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